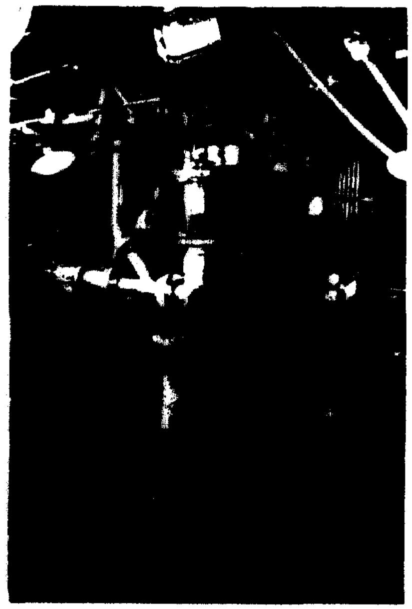
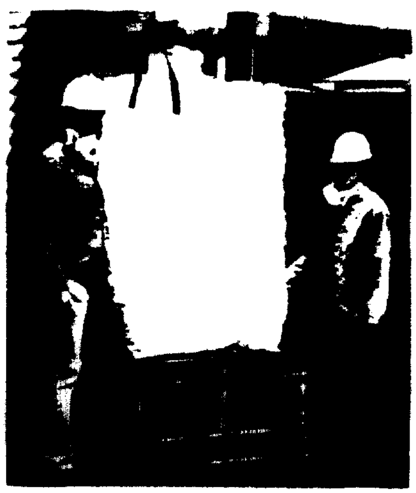
EPA

Horsehead Resource Development Company, Inc. Flame Reactor Technology

Applications Analysis Report





SITE

SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION

EPA/540/A5-91/005
May 1992

Horsehead Resource Development Company, Inc.
Flame Reactor Technology

Applications Analysis Report

Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 45268

Notice

The information in this document has been prepared for the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation program under Contract No. 68-C0-0047. This document has been subjected to EPA peer and administrative reviews and approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1986 Superfund Amendments and Reauthorization Act. The program is administered by the U.S. Environmental Protection Agency (EPA) Office of Research and Development. The purpose of the program is to accelerate the development and use of innovative cleanup technologies applicable to Superfund and other hazardous waste sites. This is accomplished through technology demonstrations designed to provide performance and cost data on selected technologies.

A field demonstration was conducted under the SITE program to evaluate the Horsehead Resource Development Company, Inc. (HRD), Flame Reactor technology. The technology demonstration took place at the HRD facility in Monaca, Pennsylvania. The demonstration effort was directed to assess the technology's ability to treat hazardous wastes based on information on the performance and cost. Documentation consists of two reports: (1) a Technology Evaluation Report, which describes the field activities and laboratory results and (2) this Applications Analysis Report, which provides an interpretation of the data and discusses the potential applicability of the technology.

A limited number of copies of this report will be available at no charge from EPA's Center for Environmental Research Information, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268. Requests should include the EPA document number found on the report's cover. When the limited supply is exhausted, additional copies can be purchased from the National Technical Information Service, Ravensworth Building, Springfield, Virginia 22161, 703/487-4600. Reference copies will be available at EPA libraries in the Hazardous Waste Collection. To inquire about the availability of other reports, call the SITE Clearinghouse hotline at 800/424-9346 or 202/382-3000 in Washington, D.C.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

Abstract

This report evaluates the Horsehead Resource Development Company, Inc. (HRD), Flame Reactor technology's ability to remove and recover volatile metals such as lead and zinc from waste while producing a vitrified slag that meets applicable disposal requirements. This report presents economic data from the U.S. Environmental Protection Agency Superfund Innovative Technology Evaluation (SITE) demonstration and seven case studies.

The HRD Flame Reactor technology is a patented high-temperature thermal process designed to treat industrial residues and wastes containing metals. During processing, the waste material is introduced into the hottest portion of the HRD Flame Reactor, where wastes are subjected to a very hot (greater than 2,000°C) reducing gas produced from the combustion of solid or gaseous hydrocarbon fuels in oxygen-enriched air. At these temperatures, volatile metals in the waste are vaporized and any organic compounds are destroyed. The waste materials react rapidly, producing a nonleachable slag and gases, including steam and metal vapors. Metal vapors further react and cool in the combustion chamber and cooling system, producing metal-enriched oxides that are collected in a baghouse. The resulting metal oxides may be recycled to recover the metals. The amount of waste reduced to slag and oxide depends on the chemical and physical properties of the waste material.

The HRD Flame Reactor technology demonstration was conducted as a part of the SITE program at the HRD facility in Monaca, Pennsylvania. For this demonstration, rotary-kiln, secondary lead smelter, soda slag was treated to produce a lead- and zinc-enriched metal oxide product and a nonhazardous (based upon present regulatory requirements) effluent slag. Greater than 75 percent of the lead, cadmium, and zinc in the waste was recovered in the potentially recyclable metal oxide product. Concentrations of lead and zinc in the oxide product were 17.4 and 1.38 percent, respectively. The effluent slag was determined to be nonhazardous based on extraction by the Toxicity Characteristic Leaching Procedure and subsequent chemical analysis of the extracts. The weight of the treated waste was reduced by 36.6 percent. During the demonstration, the Flame Reactor unit experienced no major operational problems. Several auxiliary systems had minor, repairable problems.

Potential wastes that might be treated by this technology include industrial residues, Resource Conservation and Recovery Act wastes, Superfund wastes, and other wastes contaminated with metals and organic compounds. A brief overview of the results from HRD Flame Reactor case studies, which discuss wastes that have been treated by the technology, is presented as an appendix to this report.

Economic data indicate that the cost of treating wastes similar to those treated in the HRD Flame Reactor SITE demonstration, including excavation and transportation to the HRD facility, pretreatment of the waste, and a credit of the metal oxides that are recovered, range from $208 to $932 per ton.

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List of Abbreviations, Acronyms, and Symbols

ARAR	applicable or relevant and appropriate requirements
BIF	Boiler and Industrial Furnace
brownfield site	an already developed industrial site
Btu	British thermal unit
Btu/lb	Btu per pound
°C	degrees Celsius
CCl_4	carbon tetrachloride
Cd	cadmium
Cl_2	chlorine gas
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CH_4	methane or natural gas
CO	carbon monoxide
CO_2	carbon dioxide
DOT	U.S. Department of Transportation
DRE	destruction and removal efficiency
dscf	dry standard cubic feet
EAF	electric arc furnace
EPA	U. S. Environmental Protection Agency
EP	extraction procedure
°F	degrees Fahrenheit
Fe	iron
FR	Federal Register
g	gram
H_2	hydrogen
H_2O	water
HCl	hydrogen chloride gas
hr	hour
HRD	Horsehead Resource Development Company, Inc.

List of Abbreviations, Acronyms, and Symbols (Continued)

kg	kilogram
L	liter
lb	pound
lb/hr	lb per hour
mcf	thousand cubic feet
mg	milligram
mg/L	mg per liter
N_2	nitrogen
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
ng	nanogram
ng/kg	ng per kilogram
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NSPS	new source performance standards
NSR	National Smelting and Refining Company, Inc.
NSS	North Star Steel
O_2	oxygen
ORD	EPA Office of Research and Development
OSHA	U.S. Occupational Safety and Health Administration
PaDER	Pennsylvania Department of Environmental Resources
Pb	lead
ppm	parts per million
PSA	pressure swing absorption unit
PSD	particle size distribution
psi	pounds per square inch
QA	quality assurance
QC	quality control
RCRA	Resource Conservation and Recovery Act
RD&D	Research, Development, and Demonstration
RFP	request for proposal
SARA	Superfund Amendments and Reauthorization Act
scf	standard cubic feet
SCFM	standard cubic feet per minute
sec	second
SITE	Superfund Innovative Technology Evaluation

List of Abbreviations, Acronyms, and Symbols (Continued)

SLS	secondary lead smelter
SO_2	sulfur dioxide
SO_3	sulfur trioxide
TC	Toxicity Characteristic
TCLP	Toxicity Characteristic Leaching Procedure
THC	total hydrocarbons
tpy	tons per year
TSD	treatment, storage, or disposal
Zn	zinc

Conversion Factors

	English (US)	*x*	*Factor*	*=*	*Metric*
Length:	1 inch (in)	x	2.54	=	centimeter (cm)
	1 foot (ft)	x	0.305	=	meter (m)
	1 mile (mi)	x	1.61	=	kilometer (km)
Area:	1 square foot (ft^2)	x	0.0929	=	square meter (m^2)
Volume:	1 gallon (gal)	x	3.78	=	liter (L)
	1 cubic foot (ft^3)	x	0.0283	=	cubic meter (m^3)
Mass:	1 grain (gr)	x	64.8	=	milligram (mg)
	1 pound (lb)	x	0.454	=	kilogram (kg)
	1 ton (t)	x	907	=	kilogram (kg)
Pressure:	1 pound per square inch (psi)	x	0.0703	=	kilogram per square centimeter (kg/cm^2)
Energy:	1 British Thermal Unit (Btu)	x	1.05	=	kilojoule (kJ)
	1 kilowatt hour (kWh)	x	3.60	=	megajoule (MJ)
Temperature:	(°Fahrenheit - 32)	x	0.556	=	°Celsius

Acknowledgements

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This report was prepared for EPA's SITE program by Gina Bergner, Jack Brunner, Carla Buriks, Tony Gardner, Michael Keefe, and Ken Partymiller of PRC Environmental Management, Inc., and Damian Cercone, Jeremy Flint, and John Newton, Jr. of Versar, Inc. PRC and Versar, Inc., performed the process sampling; Engineering-Science, Inc., performed the stack sampling; and Versar, Inc., performed the chemical analyses for this SITE demonstration.

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Section 1
Executive Summary

1.1 Background

In 1986, the U.S. Environmental Protection Agency (EPA) established the Superfund Innovative Technology Evaluation (SITE) Program to promote the development and use of innovative technologies to clean up Superfund sites. Technologies in the SITE Program are analyzed in two documents, the Technology Evaluation Report and this Applications Analysis Report. This Applications Analysis Report evaluates the applicability and estimates the costs of the Horsehead Resource Development Company, Inc. (HRD), Flame Reactor process based on all available data. Data not generated from the SITE demonstration were obtained from case studies provided by HRD, the technology developer. These case studies are based on 8 years of commercial-scale testing of the HRD Flame Reactor.

The most extensive testing of the HRD Flame Reactor process was performed during the SITE demonstration, which was based on a demonstration plan agreed to by EPA and the developer. The demonstration occurred at the HRD facility in Monaca, Pennsylvania, in March 1991, using rotary-kiln, secondary lead smelter (SLS), soda slag from the National Smelting and Refining Company, Inc. (NSR), Superfund site in Atlanta, Georgia. This waste was chosen as it was readily available, it contained high concentrations of several recoverable metals (lead and zinc), it contained no organics (which could not be handled under HRD's state permits), and it was representative of a waste type available in large quantities throughout the country. The HRD technology involves a high-temperature metals recovery process that produces a potentially recyclable metal oxide product and nonleachable effluent slag.

The primary objectives of the HRD Flame Reactor SITE demonstration included the following:

- Evaluate the technology's ability to treat waste materials to form a recyclable metal oxide product and a nonhazardous, fused effluent slag
- Evaluate the system's reliability
- Develop overall economic data on the technology

Secondary objectives included the following:

- Assess airborne emissions from the process
- Verify the predictions of the HRD model so that it can be used to predict costs for other projects

The purpose of this report is to provide information based on the results from the HRD SITE Demonstration and seven related case studies; this information is necessary if the HRD Flame Reactor technology is to be considered for use on Superfund and Resource Conservation and Recovery Act (RCRA) hazardous waste sites. Section 2 of this report presents an overview of the SITE program, explains how SITE program results are documented, describes the HRD Flame Reactor technology, and lists key contacts. Section 3 discusses the objectives of this SITE demonstration and briefly describes the demonstration and its findings relevant to the technology's application, including potentially applicable environmental regulations, the effects of waste characteristics and operating parameters on technology performance, material handling requirements, personnel issues, and potential community exposures. Section 4 summarizes the costs associated with implementing the technology. Appendices A through D include the following: 1) a detailed description of the HRD Flame Reactor process, 2) HRD's claims regarding the technology, 3) a summary of the SITE demonstration results, and 4) information from seven case studies prepared by HRD.

1.2 Overview of the SITE Demonstration

The HRD Flame Reactor was demonstrated at the HRD facility in Monaca, Pennsylvania, in March 1991. Seventy-two tons of waste material from the NSR site in Atlanta, Georgia, were treated during all phases of testing for the HRD SITE Demonstration. This waste material is granular, SLS slag containing carbon, iron, sodium, sulfur, lead, silicon, chlorine, zinc, arsenic, cadmium, and many other metals and inorganic chemical compounds, including water. This waste material is considered a RCRA characteristic waste because of cadmium and lead concentrations in the Toxicity Characteristic Leaching Procedure (TCLP) extracts of the waste. The waste material was dried and passed through a hammermill prior to treatment in the HRD Flame Reactor. The demonstration test runs included a series of shakedown runs to establish optimal operating conditions, a blank run with no waste treatment, four test runs (including one that was not used for interpretation of results due to sampling problems), and a series of additional runs to produce effluent slag with improved durability and to process remaining waste.

Extensive process operating data and numerous analytical samples were collected. The operating data included raw waste feed rate, processed oxide product and effluent slag production rates, natural gas and oxygen consumption rates, electrical consumption, temperatures throughout the system, and flow rates throughout the system. Laboratory analyses included analyses of the raw feed for metals, energy content, ash content, moisture, sulfur, chloride, fluoride, carbon, and total organic carbon content. Effluent samples (metal oxides from the baghouse dust and processed effluent slag) were analyzed for metals. The waste feed and effluent slag were also analyzed by the TCLP test for metals. Concentrations of carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), total hydrocarbons (THC), hydrogen chloride gas (HCl), metals, and particulate in the stack gases were also measured. Analytical data are summarized below and given in greater detail in Appendix C of this report.

1.3 Results from the Case Studies

Information HRD provided regarding the Flame Reactor technology's performance in treating other types of waste materials was evaluated to provide additional performance data. Other wastes included the following:

- Steel industry electric arc furnace (EAF) dust
- EAF dust spiked with carbon tetrachloride
- Lead blast-furnace slag
- Neutral leach residue from electrolytic zinc products
- Goethite residue from electrolytic zinc plant purification circuits
- Brass foundry Wheelabrator dusts
- SLS slag mixed with silica

Over 2,200 tons of EAF dust have been treated by the HRD Flame Reactor facility under a wide variety of process conditions. During this work, recoveries of 92 percent zinc, 95 percent lead, and 99 percent cadmium have been demonstrated. The fused effluent slag met RCRA criteria as a nonhazardous waste and, therefore, can potentially be delisted.

A test program was performed to demonstrate the ability of the HRD Flame Reactor to destroy hazardous organic contaminants when mixed with metal-bearing wastes. Carbon tetrachloride (CCl_4) was fed into the HRD Flame Reactor simultaneously with EAF dust at a loading of 5 percent of the total waste feed. The average destruction and removal efficiency was 99.9986 percent, with no CCl_4 detected in either the oxide product or effluent slag.

The HRD Flame Reactor has processed over 250 tons of two different types of lead-blast furnace slag. The goal of this test was to produce a nonhazardous, vitrified effluent slag while recovering sufficient zinc and lead to produce a recyclable product. Recoveries of 49 to 85 percent zinc and 80 to 95 percent lead were demonstrated. The vitrified effluent slag was determined to be nonhazardous.

Three test programs have been conducted at the HRD Flame Reactor facility to treat neutral leach residues from two domestic zinc plants. Recoveries of lead, silver, and zinc of 99 percent, 90 percent, and 99 percent, respectively, were demonstrated. Based on TCLP extraction tests, the fused effluent slag was determined to be a RCRA nonhazardous waste according to RCRA criteria.

The HRD Flame Reactor was used in two test programs on goethite iron precipitation residue from electrolytic zinc plants. Recoveries of lead and zinc of 93 percent and 77 percent, respectively, were demonstrated. Based on extraction tests, the fused effluent slag was determined to be a RCRA nonhazardous waste.

Two test programs were performed on brass foundry Wheelabrator dusts at the HRD Flame Reactor facility. High recovery of molten copper alloy from the slag was demonstrated. The fused slag was not a RCRA hazardous waste.

After completion of the SITE demonstration, a test program was initiated to make the effluent slag produced from the SLS slag more durable when exposed to water. Silica flour (finely ground sand) was added to the waste feed at both 12.5 and 25 weight percent to act as a fluxing agent. The resulting effluent slag from the test was found to be a RCRA nonhazardous waste. The effluent slag containing 25 percent silica sand produced a firm, glassy slag that may be suitable for use as aggregate.

1.4 Waste Applicability

The HRD Flame Reactor technology can potentially be applied to many types of granular solids, soil, flue dust, slag, and sludge containing significant concentrations of heavy metals. Wastes to be treated by the HRD Flame Reactor should be dry (less than 5 percent total moisture) and fine-grained (less than 200 mesh) to react rapidly. Larger particles (up to 20 mesh) can be processed, but they may decrease the efficiency of metals recovery or the capacity of the reactor. Wastes not meeting the moisture content and particle size criteria require pretreatment. Generally, wastes with high concentrations of metals that have a significant market value (arsenic, cadmium, cobalt, copper, gold, lead, nickel, silver, and zinc) should enhance the overall process economics. Product metal oxide can be further processed for metal recovery in industrial smelters.

1.5 Economics

An economic analysis was performed to examine 12 separate cost categories. Based on the assumptions made in the economic analysis, the estimated cost per ton for treating SLS slag ranges from $208 to $932, depending upon the quantity of waste to be treated and the location of the treatment facility (on-site or at the HRD facility). Costs presented in this analysis are order-of-magnitude estimates (-30 to +50 percent) and are rounded to the nearest dollar. Also, factors that affect the estimated cost of the HRD Flame Reactor system are highly site-specific and rather difficult to identify without accurate data from a site remedial investigation report or waste profile. Variability in the waste feed characteristics, in the costs of transporting waste to the HRD Flame Reactor, and in the costs of transporting, shipping, and handling residuals could significantly affect cost estimates.

1.6 Conclusions from the SITE Demonstration

Key findings from the HRD SITE Demonstration are as follows:

- The HRD Flame Reactor technology processed SLS slag and produced both a potentially recyclable metal oxide product and an effluent slag meeting RCRA TCLP standards.
- A site-specific risk analysis is required to assess the impact of the HRD Flame Reactor stack emissions. Based on limited data, the atmospheric emissions of metals could be a concern, however, due to data limitations, no conclusions could be reached on metal emissions.
- The HRD Flame Reactor achieved a net weight reduction of 36.6 percent when the waste feed was processed into oxide product and effluent slag.
- During the demonstration, the HRD Flame Reactor had no major operational problems; however, auxiliary systems such as the oxide product collection system, cooling water system, and feed system experienced problems that did not affect the operation of the Flame Reactor.
- The HRD thermodynamic model can be used to set preliminary operating conditions and to determine order of magnitude estimates for parameters used in a cost estimate, such as fuel and oxygen flow rates.
- The HRD Flame Reactor system processed SLS slag from the NSR site at a cost of $932 per ton. Other data from case studies show that the HRD Flame Reactor can process other types of waste for $208 per ton.

Section 2
Introduction

This section provides background information about the SITE Program, discusses the purpose of this Applications Analysis Report, and describes the HRD Flame Reactor technology. For additional information about the SITE program, this technology, and the demonstration site, key contacts are listed at the end of this section.

2.1 Purpose, History, and Goals of the SITE Program

SITE is a unique program dedicated to advancing the development, evaluation, and implementation of innovative treatment technologies applicable to hazardous wastes and hazardous waste sites. The SITE program was established in response to the 1986 Superfund Amendments and Reauthorization Act (SARA), which recognized a need for an alternative or innovative treatment technology research and development program. The SITE program is administered by EPA's Office of Research and Development (ORD).

The SITE Program is comprised of five component programs: (1) Demonstration Program; (2) Emerging Technologies Program; (3) Monitoring and Measurement Technologies Development Program; (4) Innovative Technologies Program; and (5) Technology Transfer Program. This document was produced as part of the Demonstration Program. The objective of the SITE Demonstration Program is to develop reliable performance and cost data on innovative technologies so that potential users can assess whether or not a technology is applicable for specific sites. SITE demonstrations are conducted on hazardous wastes at the actual waste sites or under conditions that closely simulate full-scale remediation conditions, thus assuring the usefulness and reliability of information collected.

Data collected during a demonstration are used to assess the performance of the technology, the potential need for pretreatment and posttreatment processing of the waste, applicable types of waste and media, potential operating problems, and approximate capital and operating costs. Demonstration data can also provide insight into long-term operating and maintenance costs and long-term risks.

Technologies are selected for the SITE Demonstration Program through annual requests for proposals (RFP). Proposals are reviewed by ORD staff to determine the technologies with the most promise for use. To be eligible, technologies must be at the pilot- or full-scale stage, must be innovative, and must offer some advantage over existing technologies. Mobile technologies are of particular interest. Cooperative agreements between EPA and the developer set forth responsibilities for conducting the demonstration and evaluating the technology. The developer is responsible for demonstrating the technology at the selected location and is expected to pay any costs to transport, operate, and remove equipment. EPA is responsible for project planning, sampling and analysis, quality assurance (QA) and quality control (QC), preparing reports, disseminating information, and transporting and disposing of treated waste materials.

2.2 Documentation of the SITE Demonstration Results

The results of each SITE demonstration are incorporated in two documents: (1) a Technology Evaluation Report; and (2) an Applications Analysis Report.

2.2.1 Technology Evaluation Report

The Technology Evaluation Report provides a comprehensive description of the demonstration and its results. It is a detailed test report intended for engineers and others making a detailed evaluation of the technology for a specific site and waste situation. This document should supply a detailed understanding of the performance of the technology during the demonstration and the advantages, risks, and costs of the technology for a given application. This information is used to produce conceptual designs in sufficient detail to make preliminary cost estimates for the demonstrated technology. This information will also aid the decision makers considering use of the technology.

2.2.2 Applications Analysis Report

The Applications Analysis Report is intended for use by decision makers responsible for implementing specific remedial actions. The principal use of the Applications Analysis Report is to assist in evaluating whether a specific technology should be considered further as an option for a particular cleanup situation. The report discusses advantages, disadvantages, and limitations of the technology. Costs of the technology for different applications are estimated based on available data for pilot- and full-scale applications. The report also discusses factors that have a major impact on performance and cost, such as site and waste characteristics.

EPA encourages the general use of demonstrated technologies by providing information on the applicability of each technology to certain sites and wastes and by studying the costs of these applications. The Applications Analysis Report assembles available information on the technology and draws reasonable conclusions about its broad-range applicability. This report is useful to those considering a technology for hazardous site cleanups; it represents a critical step in the development and commercialization of a treatment technology.

Each SITE demonstration will evaluate the performance of a technology in treating a particular waste. To obtain data with broad applications, attempts will be made to select waste frequently found at other contaminated sites. In many cases, however, the waste at other sites will differ in some way from the tested waste. Thus, the successful demonstration of a technology at one site does not ensure that it will work equally well at other sites. Data obtained from the demonstration may have to be extrapolated to estimate the total operating range in which the technology will perform satisfactorily. This extrapolation should be based on demonstration data and any other information available about the technology.

The amount of available data for the evaluation of an innovative technology varies widely. Data may be limited to laboratory tests on synthetic wastes or may include performance data on actual wastes treated as pilot- or full-scale treatment systems. In addition, there are limits to conclusions that can be drawn from a single field demonstration. A successful field demonstration does not necessarily ensure that a technology will be widely applicable or fully developed on a commercial scale.

2.3 Technology Description

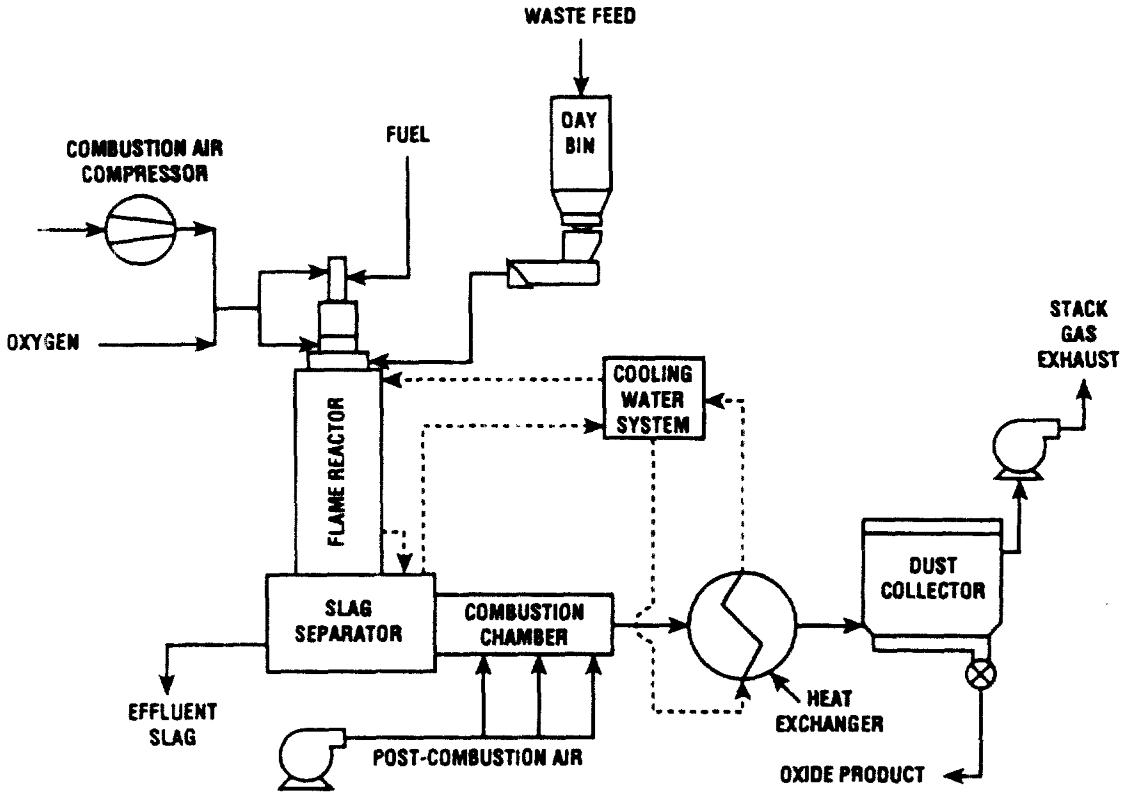
The HRD Flame Reactor process is designed to thermally treat granular solids, soil, flue dust, slag, and sludge containing metals. The treatment process yields two products: a heavy metal oxide product that can potentially be recycled by metal producers and a nonleachable, nonhazardous effluent slag that can be used as aggregate. The high-temperature reactor processes wastes with a very hot reducing gas produced from the combustion of solid or gaseous hydrocarbon fuels in oxygen-enriched air. After entering the reactor, the waste feed reacts in less than 0.5 second, allowing high waste throughput.

Metals in the waste feed, such as cadmium, lead, and zinc, are vaporized in the Flame Reactor and oxidized in the combustion chamber. These volatile metal oxides are subsequently captured downstream in a product dust collection system. Nonvolatile metals are predominantly encapsulated in the effluent slag product. For optimum reaction conditions, the waste feed should contain less than 5 percent total moisture, and at least 80 percent of the feed should be sized finer than 200 mesh. Waste material might require pretreatment by drying and physical size reduction. In order to produce a fluid slag, the fusion temperature of the nonvolatile feed materials should not exceed 1,400°C. Fluxing agents (such as sand) can be added to improve effluent slag fluidity. Variations from these specifications are acceptable but tend to decrease throughput and reduce the recovery of metals in the oxide product.

Figure 2-1 presents a schematic of the HRD Flame Reactor process. After drying and size reduction, pretreated waste material is transferred to temporary storage bins. From the temporary storage bins, the waste feed is transferred to the day bins, where it is metered by a screw feeder to a surge hopper and then pneumatically injected into the HRD Flame Reactor. In the Flame Reactor, the waste feed is heated to a high temperature (greater than 2,000°C) by the combustion of natural gas or coal and oxygen-enriched air. The high temperature forces water, volatile metals, and volatile inorganic compounds into the gas phase. Organic compounds and carbon are totally combusted. Nonvolatile and noncombustible materials are fused by the high temperatures and fall through the reactor into the horizontal slag separator. The effluent slag exits through the slag tap and then cools. Gaseous matter is drawn by reduced pressure into a combustion chamber, where air is introduced and oxidation occurs. The oxidized gases are cooled in a heat exchanger, and the metal oxide product is collected in a baghouse dust collection system. The oxide product from the dust collection system is discharged through a screw conveyor into bulk storage bags for potential recycling.

2.3.1 HRD Flame Reactor Technology Limitations

The HRD Flame Reactor technology has several limitations. At the present time, waste material must be transported to the HRD facility in Monaca, Pennsylvania, for treatment, although other HRD Flame Reactor facilities may be constructed in the future. HRD is also considering constructing a transportable unit. The HRD Flame Reactor facility in Monaca is presently permitted by an EPA Research, Development, and Demonstration (RD&D) permit that does not allow the use of the HRD Flame Reactor for certain types of commercial work. A transportable Flame Reactor unit, operating at Superfund sites, would have more flexible permit conditions. Presently, wastes containing mercury (D009) cannot be accepted for treatment, because mercury stack emissions are not captured by the current design. Other limitations of the process, such as waste feed dryness and particle size, are discussed above. HRD is presently constructing a building next to the Flame Reactor building to hold new drying and crushing equipment. A slurry feed system is also being designed as an addition to the Flame Reactor to allow a broader range of wastes to be treated.



SOURCE: Horsehead Resource Development Company, Inc.

Figure 2-1. HRD Flame Reactor Process Schematic.

2.3.2 Innovative Features of the HRD Flame Reactor Technology

The HRD Flame Reactor is a high-temperature (combustion zone temperature greater than 2,000°C) process capable of treating and recovering certain metals from wastes. Nonrecoverable metals are concentrated in a nonleachable, effluent slag that should meet EPA RCRA criteria for nonhazardous waste, allowing it to be used as aggregate or disposed of in a permitted, nonhazardous waste landfill. Air emissions from the process can be controlled with the addition of standard emission control hardware. The presence of organic compounds in the waste material should not be a problem, because at the high operating temperatures of the HRD Flame Reactor, all organic compounds should be destroyed or removed. HRD is presently pursuing options for further Flame Reactor testing of wastes containing organic contaminants. The HRD Flame Reactor design achieves a high waste feed throughput (1 to 2 tons per hour) with rapid startup and cool down (several minutes each).

2.4 Key Contacts

Additional information on the HRD Flame Reactor technology and the SITE program can be obtained from the following sources:

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Section 3
Technology Applications Analysis

3.1 Introduction

This section assesses the general applicability of the HRD Flame Reactor technology to remediate waste from various toxic waste sites. This assessment is based on the results of the SITE demonstration and data supplied by HRD. Because the results of the demonstration provide data of known quality, conclusions will be drawn mainly from the demonstration results, which are summarized in Appendix C of this report and presented in detail in the Technology Evaluation Report (U.S. EPA, 1992). Case studies supplied by the vendor are presented in Appendix D of this report.

The HRD Flame Reactor is a patented, high-temperature process designed to treat industrial residues containing metals. During processing, the waste feed is subjected to a very hot (greater than 2,000°C) reducing gas. The extreme temperature rapidly separates volatile metals (cadmium, lead, and zinc) from the remaining solid material or slag. The metal vapors are oxidized, cooled, and collected in a baghouse. The oxide product may be transferred to a metal producer for potential recycling. The goal is to produce an effluent slag that does not leach metals above the RCRA regulatory limits. If the waste feed is not a listed RCRA waste, the effluent slag can be recycled as clean fill material or disposed of in a sanitary landfill. If the waste feed is a listed waste, it must be delisted by EPA prior to disposal.

3.2 Site Demonstration Objectives

The primary objectives of the HRD Flame Reactor SITE Demonstration included the following:

- Evaluate the technology's ability to treat waste materials to form a recyclable metal oxide product and a nonhazardous fused effluent slag
- Evaluate the system's reliability
- Develop overall economic data on the technology

Secondary objectives included the following:

- Assess airborne emissions from the process
- Verify the predictions of the HRD model so that it can be used to predict costs for other projects

3.3 Summary of SITE Demonstration

In March 1991, the HRD Flame Reactor technology was demonstrated using 72 tons of rotary-kiln, SLS slag as waste feed at HRD's research facility in Monaca, Pennsylvania, 35 miles northwest of Pittsburgh. The SLS slag is a RCRA characteristic hazardous waste, because it leaches lead and cadmium above the RCRA Toxicity Characteristic (TC) limits. The SLS slag was shipped to HRD for the demonstration from the NSR waste site in Atlanta, Georgia.

The HRD research facility consists of a commercial-scale pilot plant that has been operating since 1983. The Flame Reactor process was developed for primary zinc smelting; however, subsequent testing has applied the technology to a variety of metal-bearing materials. Treating EAF dust (RCRA waste code K061) was the first commercial application for the HRD Flame Reactor technology. The HRD Flame Reactor used in this SITE demonstration has processed over 2,200 tons of EAF dust. See Appendix D of this report for more detail on EAF dust processing as well as other waste materials treated in the reactor.

The demonstration consisted of a set of shakedown runs to establish operating conditions, followed by a set of test runs using the SLS slag as waste feed. The shakedown runs, conducted in February 1991, evaluated feed rates, reactor temperatures, oxygen content of combustion air, and other parameters that had been set using a thermochemical process model.

The SITE demonstration occurred from March 17 to 23, 1991, with four 6-hour test runs and one 2-hour blank run (Run 0). During the demonstration test runs, more than 18 tons of dried and crushed SLS slag were processed. Only natural gas was burned in the reactor during the blank run. Run 1, the first test run, was discarded, because stack testing was cut short due to fluctuations in the temperature, pressure, and flow rate of the stack gases. The stack sampling results of Run 1 would not have met isokinetic sampling requirements if the sampling had continued. Runs 2, 3, and 4 consisted of three complete test runs, each with 6 hours of solids sampling and 2 hours of isokinetic stack testing.

After the demonstration, an additional study evaluated the benefits of adding silica flour (ground sand) as a fluxing agent to the remaining waste feed to increase the structural integrity of the effluent slag (see Appendix D, Case Study D-7, of this report).

3.4 Conclusions

The following overall conclusions about the HRD Flame Reactor technology are drawn primarily from the results of the SITE demonstration, but are also based on data provided by the vendor:

1. The HRD Flame Reactor technology processed SLS slag and produced both a potentially recyclable metal oxide product and an effluent slag meeting RCRA TCLP standards.
2. A site-specific risk analysis is required to assess the impact of the HRD Flame Reactor stack emissions. Based on limited data, the atmospheric emissions of metals could be a concern, however, due to data limitations, no conclusions could be reached on metal emissions.
3. The HRD Flame Reactor achieved a net weight reduction when the waste feed was processed into oxide product and effluent slag.
4. HRD cast studies suggest that metals are recovered most efficiently when the waste feed is pretreated to a PSD where 80 percent by weight is less than 200 mesh (0.0029 inch) maximum particle size.
5. The demonstration collected data only on toxic metals; however, data from another study indicate that the HRD Flame Reactor is greater than 99.9986 percent effective in destroying and removing certain organic compounds.
6. During the demonstration, the HRD Flame Reactor had no major operational problems; however, auxiliary systems such as the oxide product collection system, cooling water system, and feed system experienced problems that did not affect the operation of the Flame Reactor.
7. The HRD thermodynamic model can be used to set preliminary operating conditions to determine order of magnitude estimates for parameters used in a cost estimate, such as fuel and oxygen flow rates.
8. The HRD Flame Reactor system processed SLS slag from the NSR site at a cost of $932 per ton. Other data from case studies show that the HRD Flame Reactor can process other types of waste for $208 per ton.

These conclusions are discussed below.

1. **The HRD Flame Reactor technology processed SLS slag and produced both a potentially recyclable metal oxide product and an effluent slag meeting RCRA TCLP standards.**

   The SLS slag (waste feed) processed by the HRD Flame Reactor is a RCRA characteristic hazardous waste, because lead (RCRA waste code D008) and cadmium (RCRA waste code D006) leach above the RCRA TC limits. Lead leached at an average of 5.58 milligrams per liter (mg/L), ranging from 4.35 to 6.80 mg/L, compared to the RCRA TC limit of 5.0 mg/L. Cadmium was well above the RCRA TC limit of 1.0 mg/L, leaching at an average of 12.4 mg/L, ranging from 7.61 to 15.8 mg/L. The remaining TC metals were well below the RCRA limits for characteristic wastes. Table 3-1 presents TCLP results and RCRA TC limits for comparison.

None of the effluent slag collected during the HRD Flame Reactor Demonstration leached heavy metals above the RCRA TC limits. For cadmium, chromium, lead, mercury, and silver, TCLP values for the effluent slag were below their detection limits of 0.050, 0.060, 0.330, 0.010, and 0.050 mg/L, respectively. Selenium was below its detection limit of 0.030 mg/L for all but two samples collected during Run 2, when it exhibited TCLP values of 0.0338 and 0.0730 mg/L. Arsenic and barium were consistently above their detection limits with values ranging from 0.210 to 0.930 mg/L for arsenic and from 0.109 to 0.281 mg/L for barium. Values for all metals are well below the RCRA TC limits for characteristic hazardous wastes. Consequently, the effluent slag from the demonstration can be disposed of in a nonhazardous waste (RCRA Subtitle D) landfill.

When the HRD Flame Reactor processes EAF dust, the effluent slag, if it meets the generic exclusion levels [56 Federal Register (FR) 41164-41178], can potentially be used as a road aggregate. However, the effluent slag generated during the demonstration, although it met RCRA TC standards, disintegrated when water was added during the TCLP test procedure. Therefore, after the demonstration was complete, HRD mixed a silica flour (ground sand) with the waste feed to evaluate if the effluent slag integrity could be improved for use as an aggregate. Using a mixture of 20 percent sand by weight, the HRD Flame Reactor produced a black, glassy effluent slag that potentially could be used as a road aggregate. Use of the effluent slag as an aggregate may reduce the disposal costs of the technology; however, all applicable disposal regulations must be followed, specifically federal land disposal restriction regulations.

The technology produced an oxide product enriched in lead, cadmium, and zinc. Table 3-2 shows the composition of the waste feed, oxide product, and effluent slag. Comparing the waste feed concentrations of lead (5.41 percent weight), cadmium (0.0411 percent weight), and zinc (0.416 percent weight) with the oxide product concentrations (17.4, 0.128, and 1.38 percent weight, respectively), clearly indicates that the technology concentrates these volatile metals in the product. HRD is following several leads on the recycling options for this material.

The efficiency of the process is measured by the percent recovery of volatile metals, that is, by the

Table 3-1. TCLP Results of Waste Feed and Effluent Slag (mg/l)

Analyte	Waste Feed[a]	Effluent Slag[a]	TC Standard	RCRA Waste Code
Arsenic	0.213 (<0.210-0.264)	0.474 (<0.210-0.930)	5.0	D004
Barium	0.0347 (0.0177-0.0675)	0.175 (0.109-0.281)	100.0	D005
Cadmium	12.4 (7.61-15.8)	<0.050 (<0.050)	1.0	D006
Chromium	0.184 (0.140-0.283)	<0.060 (<0.060)	5.0	D007
Lead	5.58 (4.35-6.80)	<0.330 (<0.330)	5.0	D008
Mercury	<0.010 (<0.010)	<0.010 (<0.010)	0.2	D009
Selenium	0.0716 (<0.030-0.160)	0.0326 (<0.030-0.0730)	1.0	D010
Silver	<0.050 (<0.050)	<0.050 (<0.050)	5.0	D011

Note:

[a] Average of 18 values; range shown in parentheses

amount of a metal collected in the oxide compared to the amount in the untreated wastes. The percent recovery when processing SLS slag was greater than 75 percent for lead, cadmium, and zinc, indicating an efficient removal of volatile metals. When processing EAF dust, the HRD Flame Reactor achieved greater than 90 percent recovery for all three metals. This technology consistently appears to be able to concentrate volatile metals in an oxide product that has the potential to be recycled and reused.

2. **A site-specific risk analysis is required to assess the impact of the HRD Flame Reactor stack emissions. Based on limited data, the atmospheric emissions of metals could be a concern, however, due to data limitations, no conclusions could be reached on metal emissions.**

   For comparison purposes, Tier II screening levels of the EPA BIF regulations were compared to the HRD Flame Reactor data. The applicability of EPA BIF regulations is discussed in detail in Section 3.5, Environmental Regulations Pertinent to the HRD Flame Reactor. In summary, however, the Flame Reactor is conditionally exempt from BIF regulations. Nevertheless, because the Tier II screening levels are risk based, a state or federal permit writer could impose the omnibus authority of RCRA to protect human health and the environment [40 CFR 270.32(b)(2) and RCRA Section 3005(c)(3)] to develop standards. EPA expects most facilities to choose to comply with the Tier III standards. However, because a site-specific dispersion model is required to calculate Tier III standards, only Tier II screening levels can be presented. Tier II levels are based on a worst case dispersion model. Also, because of the short stack height at the demonstration facility, the most restrictive Tier II levels would apply to the HRD facility. A site-specific dispersion model and a stack height designed within good engineering practice criteria would probably produce Tier III standards that would be less restrictive than the Tier II levels used for this comparison.

   The HRD Flame Reactor exceeded the Tier II screening levels for lead, chromium, and arsenic. Lead was emitted at 12 grams per hour (g/hr) compared to a Tier II screening limit of 4.3 g/hr; chromium was emitted between 0.053 and 1.0 g/hr compared to a screening limit of 0.040 g/hr; arsenic was emitted between 0.27 and 0.39 g/hr compared to a screening limit of 0.11 g/hr; however, the arsenic emission values were calculated using the detection limit for samples below the detection limit. During commercial (as opposed to demonstration or research) operations, a taller stack and site-specific dispersion modeling would increase the emission standards. For example, increasing the terrain-adjusted effective stack height from 4 meters to 10 meters raises the Tier II level for lead to 13 g/hr. At this level, lead emissions (12 g/hr) would comply with Tier II screening levels.

   The HRD Flame Reactor system used in the demonstration had no acid gas emission control system. Therefore, the HCl stack gas emissions from the demonstration exceeded the Tier II screening levels. HCl was emitted at a rate between 4.85 and 5.85 grams

Table 3-2. Composition of the Waste Feed, Effluent Slag, and Oxide Product

Analyte	Waste Feed[a] (% Weight)	Effluent Slag[a] (% Weight)	Oxide Product[b] (% Weight)
Aluminum	0.596 (0.490-0.787)	1.53 (1.33-1.85)	0.0562 (0.0459-0.0623)
Antimony	0.0373 (0.0278-0.0455)	0.0357 (0.0100-0.190)	0.125 (0.122-0.131)
Arsenic	0.0515 (0.0428-0.104)	0.0262 (0.00921-0.134)	0.110 (0.101-0.117)
Barium	0.0861 (0.0804-0.0940)	0.165 (0.139-0.183)	0.0282 (0.0248-0.0323)
Beryllium	<0.00011	0.000101 (<0.000087-0.000110)	<0.00010
Cadmium	0.0411 (0.0356-0.0512)	0.000373 (<0.00023-0.00135)	0.128 (0.108-0.138)
Calcium	0.653 (0.552-0.835)	1.30 (1.06-1.45)	0.202 (0.155-0.234)
Chromium[c]	0.00877 (0.00631-0.0113)	0.00890 (0.00339-0.0385)	0.0300 (0.0278-0.0312)
Copper	0.185 (0.146-0.259)	0.344 (0.273-0.389)	0.161 (0.138-0.178)
Iron	10.3 (9.56-13.0)	20.4 (16.7-22.8)	3.22 (2.91-3.56)
Lead	5.41 (4.82-6.17)	0.552 (0.156-1.14)	17.4 (15.9-18.4)
Magnesium	0.228 (0.163-0.346)	0.543 (0.441-0.761)	0.0327 (0.0266-0.0368)
Manganese	0.0753 (0.0672-0.0903)	0.175 (0.132-0.231)	0.0265 (0.0214-0.0300)
Mercury	0.000068 (0.000054-0.000087)	<0.000010	0.000013 (<0.000010-0.000014)
Potassium	0.244 (0.204-0.284)	0.238 (0.199-0.269)	0.707 (0.630-0.751)
Selenium	0.00727 (0.00400-0.0175)	0.00344 (<0.00226-0.0176)	0.00520 (0.00415-0.00659)
Silicon3	0.276 (0.176-0.444)	0.327 (0.183-0.525)	0.127 (0.113-0.137)
Silver	0.000339 (0.000160-0.000540)	0.000394 (0.000250-0.000510)	0.00269 (0.00190-0.00342)
Sodium	12.2 (11.5-13.2)	15.5 (12.8-16.8)	15.7 (13.7-16.8)
Thallium	0.0253 (0.0181-0.0317)	0.0689 (0.0535-0.0852)	0.00746 (0.00714-0.00773)
Tin	0.282 (0.261-0.314)	0.0796 (0.0544-0.111)	0.660 (0.612-0.687)
Zinc	0.416 (0.321-0.681)	0.113 (0.0709-0.168)	1.38 (1.00-1.62)
Carbon	15.0 (9.58-19.6)	NA	NA
Chlorine as Chloride	2.46 (2.12-2.89)	NA	NA
Fluorine as Fluoride	0.0130 (0.0106-0.0166)	NA	NA
Sulfur	5.25 (4.77-6.44)	NA	NA
Moisture	3.35 (2.26-4.07)	NA	NA
Ash	81.6 (80.6-82.4)	NA	NA

Notes:

a Average of 18 values; range shown in parentheses.
b Average of 3 values; range shown in parentheses.
c Due to matrix interferences, analytical results are known to be lower than actual concentrations for the waste feed and effluent slag. When analyzed by HRD (see Appendix C of this report), chromium levels were, on average, 0.024 percent in the waste feed and 0.040 percent in the effluent slag. Silicon levels detected by HRD were, on average, 8.10 percent in the waste feed and 10.2 percent in the effluent slag.

NA = Not analyzed.
When an analyte was not detected, the detection limit was used in the calculation of the average value.

per second (g/sec), compared to a Tier II screening level of 0.091 g/sec. The addition of a wet scrubber would probably reduce the HCl emission to below the Tier II screening limit.

3. **The HRD Flame Reactor achieved a net weight reduction when the waste feed was processed into oxide product and effluent slag.**

   The secondary lead smelter slag used in the SITE demonstration achieved a net weight reduction of 36.6 percent. About 23.1 percent of this weight reduction resulted from the conversion of carbon to CO_2, moisture to steam, chloride to HCl gas, and sulfur to SO_2. The remaining 13.5 percent weight reduction is partially attributed to the liberation of oxygen from metal compounds in the waste feed, when the metal compounds were reduced by CO to metal vapor and CO_2.

4. **HRD case studies suggest that metals are recovered most efficiently when the waste feed is pretreated to a PSD where 80 percent by weight is less than 200 mesh (0.0029 inch) maximum particle size.**

   The PSD of the waste feed and the brief residence time in the reactor (between 0.1 and 0.5 seconds) affect the kinetics of the treatment reactions. Because the residence time in the reactor is very short, a small particle size is required for efficient heat and mass transfer. As the percentage of smaller particles in the waste feed increases, so does the potential reactive surface area. The greater the surface area, the more likely that volatile metals will be vaporized during treatment, thereby increasing the percent recovery of recyclable volatile metals. For the demonstration, 66.6 percent of the waste feed particles were smaller than 200 mesh (0.0029 inch or 75 microns). This PSD yielded a 77.7 percent recovery of lead. Higher percent recoveries would be expected if the PSD showed a higher percentage of particles smaller than 200 mesh.

   Case Study D-2 (Appendix D of this report) presents data comparing the percent recovery of lead and zinc from lead blast-furnace slag with two different PSDs. The milled slag (PSD 70 percent smaller than 200 mesh) exhibited 85 and 95 percent recovery for zinc and lead, respectively; the screened slag (no PSD given, but assumed coarser than the milled slag) showed 49 and 80 percent recovery for zinc and lead, respectively. For optimal reaction conditions, HRD recommends that 80 percent of the waste feed be less than 200 mesh. This can be accomplished by using a hammermill.

5. **The demonstration collected data only on toxic metals; however, data from another study indicate that the HRD Flame Reactor is greater than 99.99 percent effective in destroying and removing certain organic compounds.**

   HRD has performed tests using CCl_4 (see Appendix D, Case Study D-6, of this report). The HRD Flame Reactor achieved destruction and removal efficiencies of 99.9986 percent when the initial concentration of CCl_4 was 5 percent. Although further testing is necessary to confirm the reproducibility of these results, the high temperatures (greater than 2,000°C) at which the technology operates should be sufficient to destroy or remove most organic contaminants. Further studies of destruction of organic contaminants need to be performed

6. **During the demonstration, the HRD Flame Reactor had no major operational problems; however, auxiliary systems such as the oxide product collection system, cooling water system, and feed system experienced problems that did not affect the operation of the Flame Reactor.**

   The oxide product collection system, consisting of a shell-and-tube heat exchanger, a baghouse, an induced draft fan, and a stack, was undersized for the demonstration. The Flame Reactor was sized to handle 20,000 tons per year (tpy) of EAF dust, but the oxide product collection system was put together from surplus zinc smelter parts and cannot handle the volume of gas that would be generated from processing 20,000 tpy of EAF dust. During the demonstration, the waste feed (SLS slag) was processed at 0.9 tons per hour (7,800 tpy). The Flame Reactor system was typically shut down after about 4 hours of operation, because the oxide product collection system was undersized. For a commercial operation, the oxide product collection system would include a larger baghouse and a higher capacity induced draft fan. Because of this addition, the existing heat exchanger would not be required.

   The cooling water system also developed problems. The supply line to the shell-and-tube heat exchanger developed an underground leak. Makeup water was added to the cooling tower. This problem did not affect the operation of the reactor and would not occur during commercial operation because the heat exchanger would not be used.

   During Run 2, one of the day-bin screw feeders in the feed system jammed. For approximately 30 minutes, the other day bin was utilized at twice the normal capacity to keep the waste feed rate constant. The operation was not adversely affected.

7. **The HRD thermodynamic model can be used to set preliminary operating conditions to determine order of magnitude estimates for parameters used in a cost estimate, such as fuel and oxygen flow rates.**

   The thermodynamic model that HRD used to establish the values of the two reactor control parameters (particle residence time and reducing conditions), to calculate the operating parameters (waste feed rate, fuel flow rate, and oxygen flow rate), and to predict oxide product and effluent slag formation tares did not work well for the SLS slag waste feed. This model was developed from data for EAF dust which is different in chemical composition from the SLS slag waste feed. The parameters determined from the model were adjusted during the shakedown runs. It is recommended that the model only be used to set preliminary operating conditions and to determine order of magnitude estimates for parameters used in a cost estimate, such as fuel and oxygen flow rates.

8. **The HRD Flame Reactor system processed SLS slag from the NSR site at a cost of $932 per ton. Other data from case studies show that the HRD Flame Reactor can process other types of waste for $208 per ton.**

   The estimated cost per ton for treating SLS ranges from $208 for a 50,000 tpy waste treatment scenario that includes a more efficient waste pretreatment system than presently exists at the HRD facility to a high price of $932 for the SITE Demonstration scenario. The estimated cost of the HRD Flame Reactor system are highly site-specific and rather difficult to identify without accurate data from a site remedial investigation report or waste profile. Variability in the waste characteristics and of the costs of transporting waste to the HRD Flame Reactor and transporting, shipping, and handling residuals, could significantly affect costs presented in this economic analysis. Costs presented in the economic analysis are order-of-magnitude estimates and are rounded to the nearest dollar. A more detailed discussion of the economics of this technology is presented in Section 4. In addition, Appendix D, Case Studies, contains additional economic data.

3.5 Environmental Regulations Pertinent to the HRD Flame Reactor

This section discusses regulatory requirements pertinent to treating hazardous waste with the HRD Flame Reactor. Currently, all wastes treated by the HRD Flame Reactor are transported from remediation sites to the reactor's location in Pennsylvania. Such waste treatment is considered off-site treatment, and all substantive and administrative regulatory requirements for waste transport, storage, treatment, and disposal at the federal, state, and local level must be fulfilled. If a mobile or transportable HRD Flame Reactor is developed for on-site treatment at Superfund sites, the substantive requirements discussed in this section would be considered as applicable or relevant and appropriate requirements (ARAR); however, the administrative requirements (permits) would not have to be fulfilled.

This section discusses the permits required for the SITE demonstration project as well as regulatory requirements that would apply if the HRD operated as a fully commercialized treatment system.

Potential HRD technology users should be aware of, and make sure that they satisfy the requirements of, all applicable local, state, and federal regulations, such as RCRA revisions, the revised Clean Air Act, and state hazardous waste regulations.

3.5.1 Permits Required for the SITE Demonstration

HRD was required to obtain an EPA RD&D permit to operate the Flame Reactor for the SITE demonstration. This permit, issued in December 1990, authorizes hazardous waste research, development, and demonstration activities and satisfies the requirements of RCRA Subtitle C. The permit required HRD to prepare the following documents: 1) waste analysis plan [40 CFR 264.13]; 2) inspection schedules and logs [40 CFR 264.15]; 3) personnel training plan [40 CFR 264.16(d)]; 4) contingency plan [40 CFR 264.53(a)]; 5) operating record [40 CFR 264.73]; 6) closure plan [40 CFR 264.112(a)]; and 7) cost estimate for facility closure [40 CFR 264.142(d)]. These documents were completed by HRD and are maintained at the HRD Flame Reactor facility in Monaca, Pennsylvania.

The RD&D permit allows HRD to store hazardous wastes in containers, indoor silos, and indoor waste piles. The permit also allows HRD to treat the following RCRA-coded wastes for research purposes: D004 (arsenic), D005 (barium), D006 (cadmium), D007 (chromium), D008 (lead), D010 (selenium), and D011 (silver). No more than 160 tons of hazardous waste are permitted to be stored at the facility at any one time, and HRD must submit a research notification to EPA Region III in Philadelphia, Pennsylvania, 30 days before accepting any hazardous waste. The research notification must include the purpose of the research, the type and quantity of waste, and a residue management plan. In addition, HRD must prepare and submit to EPA a report detailing the effectiveness of all research activities and the fate of all wastes and residuals from the HRD Flame Reactor process.

The EPA RD&D permit restricts air emissions from the HRD Flame Reactor facility, limiting dust emissions from fabric filters on the storage silos and day bins as well as emissions from the baghouse. Air emissions for the Flame Reactor must also comply with permit number 04-308-028 issued by the Pennsylvania Bureau of Air Quality under the authority of the Air Pollution Control Act of January 8, 1960 [Public Law 2119], as amended.

In addition to the federal RD&D permit, HRD was granted a Hazardous Waste Storage and Treatment Permit through the Pennsylvania Department of Environmental Resources (PaDER) in August 1990. This permit authorizes management of hazardous waste for research, development, and demonstration purposes. Specific permit conditions include restrictions on operating conditions, types of wastes treated, and storage of hazardous waste in containers, tanks, and waste piles.

PaDER required HRD to submit a Module 1 permit application for the waste storage and treatment activities conducted during the SITE demonstration. This permit identified the source, characteristics, and volume of waste HRD treated during the demonstration. Both EPA and PaDER authorized temporary waste pretreatment (drying and crushing) for the SITE Demonstration.

3.5.2 Federal ARARs

The U.S. Department of Transportation (DOT) requirements for transporting hazardous waste must be met when wastes are transported to the HRD Flame Reactor. Transportation regulations apply to both research-scale or commercial-scale operation of the HRD Flame Reactor. In addition, Occupational Safety and Health Act (OSHA) requirements [29 CFR Parts 1900 through 1926] provide for the health and safety of workers at hazardous waste treatment facilities and hazardous waste sites and must be fulfilled at both the research-scale and commercial-scale level of operation.

On August 21, 1991, the EPA BIF rule [40 CFR 266, Subpart H] became effective. The HRD Flame Reactor is classified as a smelting, melting, and refining furnace by the BIF rule [56 FR 7143]. However, smelting, melting, and refining furnaces that process hazardous waste solely for metal recovery are conditionally exempt from the majority of 40 CFR 266, Subpart H regulations, and therefore, need only comply with 40 CFR 266.101 (Management Prior to Burning) and 40 CFR 266.112 (Regulation of Residues). These furnaces are conditionally exempt because 1) EPA does not believe it prudent to regulate a whole potential class of devices and wastes that it has not fully evaluated and 2) EPA wishes to study further whether regulating these furnaces under the Clean Air Act may be more appropriate, specifically if technology-based controls on toxic air emissions are likely to apply.

Even though EPA might classify the HRD Flame Reactor as conditionally exempt, because the BIF rule promulgated risk-based emission levels for metals and HCl, the state or federal permitting authority could apply these standards by imposing the omnibus authority of RCRA [40 CFR 270.32(b)(2) and RCRA Section 3005(c)(3)] to protect human health and the environment. Therefore, the BIF regulatory limits for metals, HCl, and particulate emissions are presented below.

The BIF rule established a three-tiered permitting structure to control emissions of HCl, chlorine (Cl_2), and 10 toxic metals listed in Appendix VIII of 40 CFR 261. The list of 10 toxic metals is further broken down into four carcinogenic metals (arsenic, beryllium, cadmium, and chromium) and six noncarcinogenic metals (antimony, barium, lead, mercury, silver, and thallium). Tier I of the three-tiered permitting structure limits feed rates, Tier II sets emission rate screening limits, and Tier III requires a site-specific risk assessment. EPA expects the majority of facilities to elect to comply with Tier III standards to obtain more flexible permit limits.

Tier III standards require 1) emissions testing to determine the emission rate for each metal and 2) air dispersion modeling to predict the maximum, annual, off-site, ground-level concentration for each metal. These concentrations are then compared to the acceptable ambient levels specified in Appendix IV and V of the BIF rule [56 FR 7223]. The cost and time estimates to perform Tier III metal emission assessments are considerable. These calculations are both waste and site specific and must be done on a case by case base. Future HRD Flame Reactor work might not be done at Monaca, Pennsylvania - and the calculations would have to be redone. While this calculation is definitely desirable, its cost is prohibitive and beyond the scope of this SITE project. If the AAR reader is very interested in the HRD technology, he can contact HRD and discuss concerns before selecting this technology. Therefore, in this report Tier II screening limits will be presented. These limits are not the regulatory limits for the Flame Reactor and are presented for comparison purposes only. In addition, because the HRD stack is shorter than the Flame Reactor building, and because the surrounding terrain within 5 kilometers (3.1 miles) of the stack equals or exceeds the elevation of the physical stack height, the Tier II screening limits presented below [56 FR 7229, 7230, 7232] are the conservative (restrictive) limits.

Carcinogenic Metals	Tier II Screening Limits
Arsenic	0.11 g/hr
Cadmium	0.26 g/hr
Chromium	0.040 g/hr
Beryllium	0.20 g/hr
Noncarcinogenic Metals	
Antimony	14 g/hr
Barium	2400 g/hr
Lead	4.3 g/hr
Mercury	14 g/hr
Silver	140 g/hr
Thallium	14 g/hr
HCl and Cl_2	
HCl	330 g/hr or 9.1×10^{-2} g/sec
Cl_2	1.9 g/hr or 5.2×10^{-4} g/sec

The HRD Flame Reactor may be subject to additional air emissions regulations when the Clean Air Act Amendments of 1990 are promulgated. The Clean Air Act Amendments concerning hazardous air pollutants may potentially address many of the same sources regulated under 40 CFR 266. For example, the New Source Performance Standards (NSPS) of Section 111 of the Clean Air Act may be ARARs for a HRD Flame Reactor unit installed at a Superfund site, especially if the pollutants emitted and the technology employed are sufficiently similar to a pollutant and source category regulated by the NSPS. Also, EPA has established National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for arsenic, beryllium, and mercury for certain categories of sources [40 CFR 61].

3.5.3 State and Local Regulations

State and local regulatory agencies may write permits that are more stringent than the federal regulations. Therefore, state and local regulations have to be evaluated on a case-by-case basis.

3.6 The Impact of Waste Characteristics on the Performance of the Technology

Waste feed characteristics affecting the efficiency of the HRD Flame Reactor include PSD, moisture content, chemical composition, and fusion temperature.

HRD recommends that 80 percent of the waste feed should be finer than 200 mesh (0.0029 inches or 75 microns); however, waste feed with a PSD of up to 80 percent smaller than 30 mesh (600 microns) has been processed. Coarser waste feed may decrease efficiency and impede slag fusion, both of which decrease the recovery of volatile metals. HRD operates a hammermill for feed size reduction.

The recommended moisture content is less than 5 percent total moisture; however, waste feeds with up to 15 percent total moisture have been processed effectively. Low moisture content requires less energy, and the gravity and pneumatic feed system requires low moisture content for reliable operation. HRD operates a steam-heated, hollow auger unit for waste feed drying.

The chemical composition of the waste feed affects the Flame Reactor's energy consumption, the reducing or oxidizing condition in the reactor, and the possible need to add a fluxing agent to achieve a more efficient process. The type and concentration of volatile metals present in the waste feed is another important characteristic of the chemical composition. HRD recommends a total volatile metal content of 5 percent or greater in order to produce an oxide product with a reasonable metal content for recycling.

The fusion temperature or melting point of the waste feed should be lower than 1,400°C to ensure that the waste will melt. The slag separator operates between 1,400°C and 1,600°C. If the fusion temperature is too high, the effluent slag will begin to solidify in the reactor. Fluxing agents can be added to reduce the fusion temperature and viscosity.

3.7 The Impact of Operating Parameters on the Performance of the Technology

The HRD Flame Reactor process can be adjusted to regulate two control parameters: 1) the residence time of the feed particles in the reactor and 2) the reducing conditions in the reactor. These two control parameters are regulated by the three operating parameters: 1) waste feed rate, 2) fuel feed rate, and 3) oxygen content of combustion air. Optimal conditions for these three operating parameters were determined in the shakedown runs to achieve the desired residence time and reducing conditions. The reactor temperature is not a control parameter and it cannot be measured directly. It can only be controlled indirectly by manipulating one or more of the operating parameters.

The waste feed rate affects the residence time of the particles in the reaction zone, as well as the quantity of metal oxide in the off-gas. If the residence time is reduced too much (that is, the feed rate is too high) the feed particles will only partially reduce. Partial reduction of the feed particles will lower the percentage of volatile metals recovered in the oxide product and will produce a slag with a higher concentration of volatile metals.

The fuel feed rate controls the source of the reducing gas stream and the amount of energy available for feed fusion. When the fuel feed rate is higher, more CO is present to reduce the metals to elemental form; higher reducing conditions in turn increase the percent recovery of volatile metals. The combustion (oxidation) of the fuel provides the energy for the fusion of the waste feed. Sufficient energy must be provided to completely fuse the waste feed into a fluid slag.

The O_2 content of the combustion air affects 1) the stoichiometric conditions that produce the reducing gas stream and 2) the volume of the off-gas stream. Although the fuel feed rate controls the source (CO) and the amount of the reducing gas stream, the O_2 content determines the extent of oxidation of the fuel. A low O_2 content produces higher reducing conditions because not all of the fuel is oxidized to CO_2, and much of it remains as CO. A high O_2 content produces lower reducing conditions, because most of the fuel is completely oxidized to CO_2. However, a high O_2 content decreases the volume of gas in the oxide product collection system, because it lowers the volume of combustion air required. The HRD Flame Reactor typically operates at between 50 and 80 percent O_2 (ambient air is 21 percent). During the demonstration, the O_2 content averaged 83 percent.

Although it is not a control parameter, the reactor temperature affects the reaction rate. At higher temperatures, reaction rates increase, allowing shorter residence times and increased feed rates. However, higher reactor temperatures increase heat losses, and high heat losses require more fuel and O_2 to maintain a given reaction temperature.

3.8 Materials Handling Required by the Technology

HRD performs all materials handling at the HRD Flame Reactor facility. If necessary, the waste is pretreated to achieve optimal PSD and moisture content, before being transferred to the day bins. During treatment in the Flame Reactor, the waste feed, fuel, O_2, and compressed air entering the system must be fed and metered. After treatment, both effluent streams require special handling.

Waste feed pretreatment consists of drying and reducing the particle size. Following pretreatment, waste feed is placed in portable storage bins that are stored adjacent to the reactor building until required. The waste feed is mechanically conveyed from the portable bins to the day bins located above the reactor in the Flame Reactor building. During treatment, the waste feed is metered by screw conveyors and pneumatically injected into the reactor.

Natural gas or another fuel source, O_2, and compressed air are metered into the reactor. O_2 is stored on site as a cryogenic liquid in a 9,000-gallon storage tank; natural gas is supplied by the local utility company through a pipeline; and compressed air is supplied by a rotary compressor located adjacent to the Flame Reactor building.

The oxide product requires special handling because of its high heavy metal content. The oxide collection system collects the oxide in 1.5-cubic-yard bulk storage bags (supersacks) filled directly from the conveyor to minimize worker dust exposure. When one supersack becomes full, the conveyor begins to fill another. After the supersack is removed from the recovery system, the sack can manually be closed to prevent dust from escaping.

The effluent slag requires special handling because of its extreme heat. The effluent slag is about 1,400°C when it is tapped from the separator. It falls onto a 25-foot-long, vibrating, water-cooled conveyor. At the end of the conveyor, the slag, now about 600 to 800°C, drops into a metal collection bin. When the collection bin is full, a forklift moves it to the storage building for additional cooling.

3.9 Community Impact

Because the facility is located in an industrial area, the impact of the HRD Flame Reactor on the community surrounding the HRD facility is minimal. The hazards to the community may include the following:

- Stack emissions
- Dust releases
- Transportation hazards

Stack emissions from the Flame Reactor are low and will be reduced even further when new emission control equipment is purchased. Dust releases from both pretreatment and Flame Reactor processing are minimal due to the dust control equipment used at the facility. Transportation hazards are minimal, because the waste feeds are typically solids and are generally stored in closed containers.

3.10 Personnel Issues

During test program operations, the HRD Flame Reactor operates two 8-hour shifts per day. A shift supervisor, two operators per shift, and a mechanic are needed to run the HRD Flame Reactor plant. At the HRD Flame Reactor facility, self-extinguishing coveralls, half-face respirators, hard hats, steel-toe shoes, and safety glasses are required; in addition, hearing protection is suggested. Special protective clothing is required to protect the worker at the slag tap hole from the intense heat. Safety showers, emergency eye-wash stations, first aid kits, and fire prevention equipment are located throughout the facility.

The HRD Flame Reactor contains many safety features in its design. The system is designed to automatically shut itself down when problems occur or when the range of predetermined operating conditions is exceeded. Nitrogen can be introduced into the Flame Reactor system instantly to displace air and O_2 if explosive conditions ever occur. Explosive conditions might occur if the burner system failed to ignite.

Section 4
Economics

One goal of the SITE program is to develop reliable cost data for innovative and commercially available hazardous waste treatment. Cost data for the HRD Flame Reactor technology were obtained primarily from HRD. Other sources of cost information included EPA experience and the SITE demonstration. The costs associated with the HRD Flame Reactor technology have been placed into the 12 cost categories applicable to typical cleanup activities at Superfund and RCRA corrective action sites. These cost categories are defined and discussed in this section as they apply to the HRD Flame Reactor technology. Table 4-1 presents estimated costs per ton for waste treated by six HRD Flame Reactor scenarios. These six scenarios are divided into the SITE Demonstration test operating conditions (Scenario 1) and five commercial operating scenarios (Scenarios 2 through 6). Scenarios 1, 2, and 4 are based on waste treatment at the HRD facility in Monaca, Pennsylvania, and Scenarios 3, 5, and 6 are based on treatment at the waste location. Costs presented in this analysis are order-of-magnitude estimates (-30 to +50 percent) and are rounded to the nearest dollar.

4.1 Site-Specific Factors Affecting Cost

A number of factors affect the cost of the HRD Flame Reactor system. These factors are highly site-specific and rather difficult to quantify without accurate data from a site remedial investigation report or waste profile. Factors affecting costs generally include 1) the volume of waste to be treated; 2) waste characteristics such as waste feed PSD, moisture content, and type and concentration of contaminants in the waste; 3) the distance the waste must be transported to the HRD Flame Reactor; 4) treatment goals to be met; and 5) frequency of equipment repair and replacement.

4.2 Basis of Economic Analysis

The HRD Flame Reactor technology can be applied to several types of wastes, including granular solids, soil, flue dust, slag, and sludge containing heavy metals. This economic analysis is based on SLS slag as the waste feed to be treated. It should be noted that all the cost categories for the secondary lead slag scenario may not apply to other types of waste. Therefore, when estimating the costs for a given scenario, only applicable categories should be used.

For the purpose of this economic analysis, the HRD Flame reactor is assumed to operate 24 hours per day, 7 days per week, operating 85 percent of the time. Therefore, 6,700 tpy (Scenarios 1 through 3), 13,400 tpy (Scenario 4), 20,000 tpy (Scenario 5), and 50,000 tpy (Scenario 6) correspond to 0.9, 1.8, 2.7, and 6.7 tons of waste feed per hour, respectively. Also, the HRD Flame Reactor unit is assumed to have a 10 year life.

For this analysis, certain assumptions, derived from the HRD SITE Demonstration, were made regarding the waste feed and the operating conditions. Assumptions regarding waste transportation apply only to treatment at the HRD Monaca facility (Scenarios 1, 2, and 4) and not to on-site treatment at a waste site (Scenarios 3, 5, and 6). These assumptions include:

<u>Assumptions Regarding the Untreated Waste Feed</u>

- Waste must be excavated at the site.
- The hazardous waste site is within 750 miles of the HRD facility in the Monaca, Pennsylvania, scenarios.
- The particle size of the raw waste will require size reduction to less than 200 mesh for the commercial scenarios. The largest particle size in the demonstration test was 30 mesh.
- The moisture content of the waste is between 15 and 25 percent, and the waste must be dried to 5 percent total moisture.
- The waste is primarily contaminated with heavy metals (such as lead and cadmium) at levels up to 7.5 percent.
- No pretreatment of the waste is required, other than crushing or grinding, drying, and screening.

<u>Assumptions Regarding the Operating Conditions</u>

- Technicians will collect all samples and perform equipment maintenance and minor repairs.
- Labor costs associated with major equipment repairs or replacement are included.
- Waste feed rates for the system varies between 0.9 and 6.7 tons per hour in the scenarios.
- Fuel to waste feed ratio for the system is 8.4 to 23.1 thousand cubic feet (mcf) of natural gas per ton.

Table 4-1. Estimated Costs Associated With HRD Flame Reactor Systems

Operating Scenario	SITE Test			Commercial Operations (scenarios 2-6)		
Scenario Number	1	2	3	4	5	6
Plant Location	Monaca	Monaca	On-Site	Monaca	On-Site	On-Site
Capital ($ million)	2.5	2.5	3.1	4.5	6.0	10.4
Annual Capacity (tons)	6,700	6,700	6,700	13,400	20,000	50,000
Cost Categories			**Estimated Costs per Ton of Waste Treated (1991 $)**			
Site Preparation						
Excavation of Waste	93	10	10	10	10	10
Transportation of Waste	129	60	6	60	6	6
Pretreatment of Waste	246	21	21	20	19	17
Permitting and Regulatory Requirements	10	10	10	10	10	10
Capital Equipment	64	64	79	58	52	36
Startup	1	1	1	1	1	1
Labor	114	78	93	39	31	18
Consumables						
O_2	131	93	93	60	49	41
Natural Gas	81	58	58	34	26	21
Utilities	11	11	11	11	11	11
Effluent Monitoring [a]	0	0	0	0	0	0
Shipping, Handling, and Transporting Residuals						
Effluent Slag	15	15	15	15	15	15
Oxide Product [b]	–	–	–	–	–	–
Analytical Testing	3	3	4	2	2	1
Equipment Repair and Replacement	34	34	37	30	24	15
Site Demobilization	0	0	10	0	7	6
Total Cost Per Ton Waste	**$932**	**$458**	**$448**	**$350**	**$263**	**$208**

Notes:

[a] Costs for effluent monitoring are included in capital and labor cost categories.
[b] The credits or costs for disposal of oxide product are still being evaluated.

- The O_2 content of the combustion air is 83 percent in the demonstration test and 80 percent for all of the commercial scenarios.
- The HRD Flame Reactor temperature will be greater than 1,650°C for all scenarios.
- The HRD Flame Reactor CO/CO_2 ratio is 20:7.

4.2.1 Site Preparation Costs

The HRD Flame Reactor facility in Monaca, Pennsylvania, is a stationary unit, requiring waste to be brought to the facility for treatment. Therefore, typical site preparation costs such as site design, planning and management, legal searches, access rights, and construction work that would normally be involved in setting up the system at a hazardous waste site are not applicable. However, site preparation costs include excavation of waste, transportation of waste to the HRD facility, and pretreatment of waste. Site preparation costs for the on-site scenarios are also presented for these tasks so that comparisons can be made among the commercial scenarios.

Site preparation costs will vary depending on the type, condition, and geographical location of the site. Sites where excavation is difficult or sites that require waste transportation beyond 750 miles will have significantly increased site preparation costs. Also, waste that requires extensive pretreatment will increase costs in this category.

For the demonstration test, site preparation costs were $468 per ton of waste. Costs included the following: 1) $93 per ton for excavating the waste with a backhoe and loading the waste into 1-cubic-yard bulk sacks and 2) $129 per ton for transporting 72 tons of the waste 750 miles to the HRD facility. In the commercial scenarios, excavation cost are significantly reduced by economy of scale.

Costs for commercial-scale pretreatment differ significantly from costs for the demonstration test. Commercial scale pretreatment costs totalled $246 per ton and included $200 per ton for labor, $13 per ton for utilities, and $33 per ton for rental of a waste feed dryer and hammermill. Commercial scale pretreatment equipment will reduce pretreatment costs by reducing labor costs.

4.2.2 Permitting and Regulatory Costs

Permitting and regulatory costs will vary depending on whether treatment is performed on a Superfund or a RCRA corrective action site and the fate of the treated waste. Section 121(d) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by SARA, requires that remedial actions be consistent with ARARs of environmental laws, ordinances, regulations, and statutes. ARARs include federal standards, as well as more stringent standards promulgated under state or local jurisdictions. ARARs must be determined on a site-specific basis.

The HRD facility is a permitted RCRA treatment, storage, or disposal (TSD) facility. The cost of keeping up with applicable regulations is estimated to be about $10 per ton for all cases. Permitting and regulatory costs for waste and treatment residues transported to and from the facility are not included in this estimate.

4.2.3 Capital Equipment Costs

Capital equipment costs include the cost of the HRD Flame Reactor and the required auxiliary equipment. The capital costs shown in Table 4-1 are based on information provided by HRD and assume financing at 12 percent per year over 10 years.

4.2.4 Startup Costs

Startup costs for the HRD Flame Reactor scenarios include purging the system and establishing operating parameters for the waste stream. These costs would be primarily for labor. Purging the system could also be considered demobilization from the previous run; therefore, startup costs are estimated to be about $1 per ton of waste treated and, for treatment at Monaca (Scenarios 1, 2, and 4), no demobilization cost is required. This cost is based primarily on labor costs for five technicians working three shifts each on 3 operating days for this activity.

On-site startup costs are based on 1 month of labor costs and are spread over a 10 year plant life. Actual costs would be case specific and would vary with site conditions and the length of the remediation period.

4.2.5 Labor Costs

HRD estimates a Flame Reactor operating crew of three workers per shift for the 50,000 tpy scenario (Scenario 6), and two workers per shift for other scenarios. One mechanic and one supervisor are required, except for the 50,000 tpy plant, where two mechanics are required. Two additional workers are added to the on-site scenarios to handle reporting and clerical needs. All personnel work a 40-hour week at an average hourly rate of $25.

4.2.6 Consumable Costs

Consumable costs for the HRD Flame Reactor system include costs for O_2 and natural gas. The quantities used will depend on the waste feed rate, the O_2 content of the combustion air, the reactor temperature, and the scale of operation. The commercial scenarios assume bulk pricing at $2.50 per mcf for both O_2 and natural gas (compared to $3.50 per mcf for noncommercial scenarios). The consumable costs are estimated to be approximately $41 to $131 per ton of O_2, and $21 to $81 per ton of natural gas.

4.2.7 Utility Costs

The HRD Flame Reactor system requires 480-volt, three-phase electric power. The electric power requirements will be primarily for motors and pumps in the system. Electric power cost is estimated at $11 per ton for all scenarios. Water costs are considered negligible, because water is recycled in the system.

4.2.8 Effluent Monitoring Costs

This cost category covers monitoring the system's air emissions according to the facility's air permit. Effluent monitoring will be performed by the HRD Flame Reactor system operators. Effluent will be discharged to the atmosphere according to limits set by local and state regulations. Costs for monitoring effluent are included in capital and labor cost categories.

4.2.9 Residuals Shipping, Handling, and Transportation Costs

The HRD Flame Reactor system produces an oxide product and an effluent slag that require special handling and disposal. Costs for this disposal will depend on geographic location, distance from the site to the permitted landfill, as well as other factors such as the concentrations of regulated metals in the oxide product and effluent slag.

Residual slag shipping, handling, and transportation costs are based on the generation of about 30 tons of slag per 100 tons of waste treated. The estimated disposal cost is approximately $15 per ton of waste treated. The actual disposal cost is $45 per ton of effluent slag and includes transportation, disposal, and other customary charges for transportation and disposal of the effluent slag to a sanitary waste landfill within 100 miles of Monaca, Pennsylvania.

The oxide product from the baghouse was collected and analyzed and subsequently can potentially be recycled for recovery of its lead content. There may be a cost involved in recycling the lead oxide dust. This cost depends on the current lead market (supply and demand for lead), the concentration of lead as well as impurities or contaminants in the material to be recycled, the amount of oxide product, and the cost of handling the oxide product. It should be noted that the amount of oxide produced during the demonstration was approximately 25 weight percent of the total dried waste feed.

4.2.10 Analytical Costs

Analytical costs include those for laboratory analysis, data reduction and tabulation, QA/QC, and reporting. These costs are for verification of treatment effectiveness and do not include waste characterization. Analytical costs will vary according to the types of contaminants and regulatory requirements for the waste.

This analysis assumes that daily composite samples of oxide product and effluent slag will be collected and analyzed for the major species of concern (such as lead) using energy dispersive x-ray fluorescence. Weekly composite samples will also be collected and analyzed using TCLP, depending on the customers' request. This results in analytical costs of about $1 to $4 per ton of waste treated.

4.2.11 Equipment Repair and Replacement Costs

During the course of operation, some parts of the system may require repair or replacement. For this analysis, equipment repair and replacement costs vary from 9 percent of capital costs or about $34 per ton of treated waste for the 6,700 tpy scenarios (Scenarios 1 through 3) to 7 percent of capital for the 20,000 and 50,000 tpy scenarios (Scenarios 5 and 6, respectively). This cost includes any major repairs or replacements.

4.2.12 Site Demobilization Costs

Site demobilization normally includes items such as operation shutdown and decommissioning of equipment, site cleanup and restoration, and disconnection of utilities. The HRD Flame Reactor facility at Monaca will not be decommissioned after treating the waste and this cost category would only involve purging the system. This purging can also be considered startup costs for the subsequent run. Therefore, for the Monaca scenarios, demobilization costs are included in startup costs.

For the on-site scenarios, demobilization includes 6 months of labor and other decommissioning costs spread over a 10-year operating life.

4.3 Summary of Economic Analysis

Considering the 12 cost categories and the assumptions made in this economic analysis, the estimated cost per ton for treating SLS slag ranges from $932 for the SITE Demonstration (Scenario 1) to $208 for a 50,000 tpy scenario (Scenario 6), which includes a waste pretreatment system for more efficient waste processing in the HRD Flame Reactor. The waste pretreatment system increases capital costs per ton of waste treated by about 36 percent; however, this system decreases pretreatment costs by 91 percent, labor costs by 50 percent, consumables costs by 43 percent, and equipment repair and replacement costs by 12 percent. HRD expects to have the pretreatment system for its Flame Reactor in place by 1992.

As mentioned earlier in this section, costs presented in this analysis are order-of-magnitude estimates (-30 to +50 percent) and are rounded to the nearest dollar. Also, factors that affect the estimated cost of the HRD Flame Reactor system are highly site-specific and rather difficult to identify without accurate data from a site remedial investigation report or waste profile. Variability in the waste characteristics, in the costs of transporting waste to the HRD Flame Reactor, and in transporting, shipping, and handling residuals could significantly affect costs presented in this economic analysis.

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Appendix A
HRD Flame Reactor Process Description

Appendix A
HRD Flame Reactor Process Description

A.1 Background

The Horsehead Resource Development Company, Inc. (HRD) Flame Reactor process is designed to thermally treat metal-containing solids, soil, flue dust, slag, and sludge. The treatment process yields two products: a heavy metal-enriched oxide product that can potentially be recycled by metal producers and a vitrified slag that can potentially be used as an aggregate. The HRD high-temperature reactor processes wastes with a very hot reducing gas produced from the combustion of solid or gaseous hydrocarbon fuels in below stoichiometric O_2-enriched air. Upon injection into the reactor, the feed materials are believed to react in less than 0.5-second, allowing a high waste throughput.

Volatile metals, such as cadmium, lead, and zinc, in the waste material are vaporized and captured downstream in a product dust collection system. Nonvolatile metals, such as chromium, iron, and nickel, are encapsulated in the slag. For good reaction conditions, the particles should contain less than 5 percent total moisture, and at least 80 percent of the feed should be less than 200 mesh. Also, the feed material's fusion temperature should not exceed 1,400°C. Variations from these specifications are acceptable but tend to decrease throughput and reduce the percent recovery of metals in the oxide product.

Figure A-1 presents the process flow diagram for the HRD Flame Reactor process. The process consists of five sections:

- Feed System
- HRD Flame Reactor
- Slag Separator
- Combustion Chamber
- Oxide Product Recovery System

The five sections are discussed below.

A.2 Feed System

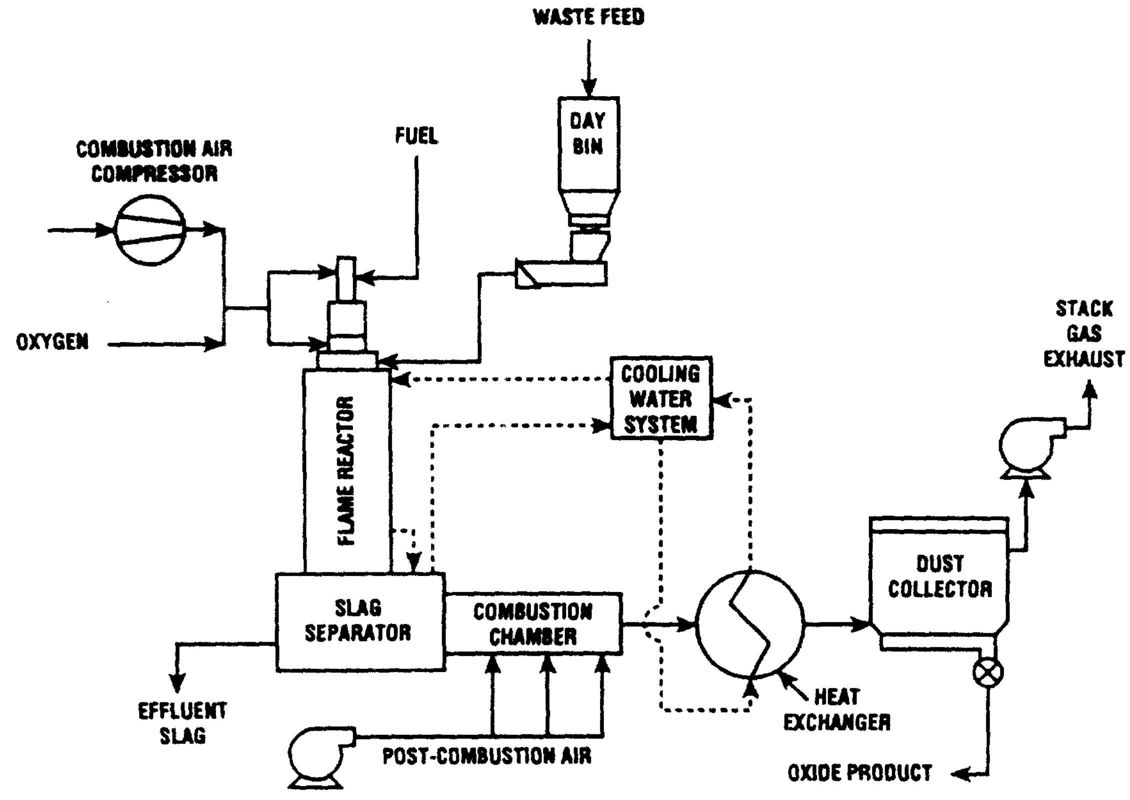
Feed system operations include 1) waste feed and solid fuel storage and handling, 2) metering and injection of waste feed and fuel into the reactor, and 3) metering and injection of O_2 and air.

The solid material storage and handling system consists of storage facilities, portable bins, day bins, and a pneumatic conveying system. The waste material to be fed into the reactor can be delivered to the site by rail or by truck. The waste material is stored in a storage building next to the Flame Reactor building prior to processing. If pretreatment of the waste (drying and crushing) is necessary, the waste is transferred to another building that contains the pretreatment equipment. After pretreatment, a loader empties the feed material into portable bins, which are moved to the HRD Flame Reactor building. From the portable bins, waste is transferred to the day bins by placing the portable bin on a discharge stand and opening the bottom discharge slide-gate of the portable bin. Dusting is controlled by a seal located between the gasketed opening of the stand and the flange of the portable bin slide-gate. The waste is fed into a screw conveyor that empties into the tubular, day bin filling system.

Of the three day bins, two are used for waste, and one is used for solid fuel. Normally, solid fuel such as coal fines can be used to reduce costs; however, natural gas was chosen for the SITE demonstration because 1) it is more likely to be used in a site remediation and 2) it has a uniform composition. Each day bin has a capacity of 150 cubic feet and is mounted on a set of three, shear-beam, load cells that measure the day bin weight for inventory and process control. Material from each day bin is pneumatically injected into the reactor.

To calculate waste feed rate, the process control system records the loss of weight over time. The system uses a 10-minute average waste feed rate to control the feed system. Material is discharged from a day bin, through a live-bottom feeder, into a surge hopper set above a variable speed screw feeder with a rated capacity of 60 pounds per minute. The feeder accurately controls the flow of material into the reactor via a 2-inch, pneumatic injection line.

The gases used in the SITE demonstration were O_2, ambient air, and natural gas. O_2 is stored on-site as a cryogenic liquid in a 9,000-gallon storage tank. The O_2 is used to enrich the ambient air for combustion. Compressed air produced by a compressor, operating at 1000 standard cubic feet per minute (SCFM) at 40 pounds per square inch (psi), is used to convey the solid feeds to the reactor and to combust the fuel. Natural gas, supplied by pipeline from the local utility company, was used as the fuel during this



SOURCE: Horsehead Resource Development Company, Inc.

Figure A-1. HRD Flame Reactor Process Schematic.

demonstration. A 6,000-gallon liquid N_2 tank is also on-site, but it was not used in the demonstration. The N_2 is used to blanket coal fines as an added safety feature when coal is used as the fuel source.

A.3 HRD Flame Reactor

The HRD Flame Reactor, shown in Figure A-2, is a two-stage system consisting of a fuel burner system (first stage) and the metallurgical reactor (second stage). Carbon-based combustion and gasification reactions occur in the burner system, followed by metal smelting reactions in the metallurgical reactor. The reactor is 15 feet tall, positioned vertically, with an internal diameter of 23 inches.

The first stage of the Flame Reactor is a fuel burner system consisting of a mixing head, upper pilot, lower pilot, and gas injection chamber. In the mixing head, fuel and O_2-enriched air (typically 50 percent to 80 percent O_2 by volume) are mixed. This mixture then ignites in the upper pilot and is stabilized by expansion into the lower pilot. Injecting O_2-enriched air in the gas injection chamber helps control the reducing conditions, adjust the stoichiometry ($CO:CO_2$ ratio), and further stabilize the flame in the Flame Reactor. Because highly O_2-enriched air is used, flame temperatures greater than 2,000°C are realized in the Flame Reactor. A different burner design is employed when solid fuel is used as the energy source.

Fine, dry, waste feeds containing metals are metered with a screw feeder and pneumatically injected into the reactor (second stage) at a location just below the exit of the burner (see Figure A-2). The waste feed reacts in the high-temperature, reducing gas stream. CO from the incomplete combustion of the fuel reduces the metal compounds in the waste feed by the following reactions:

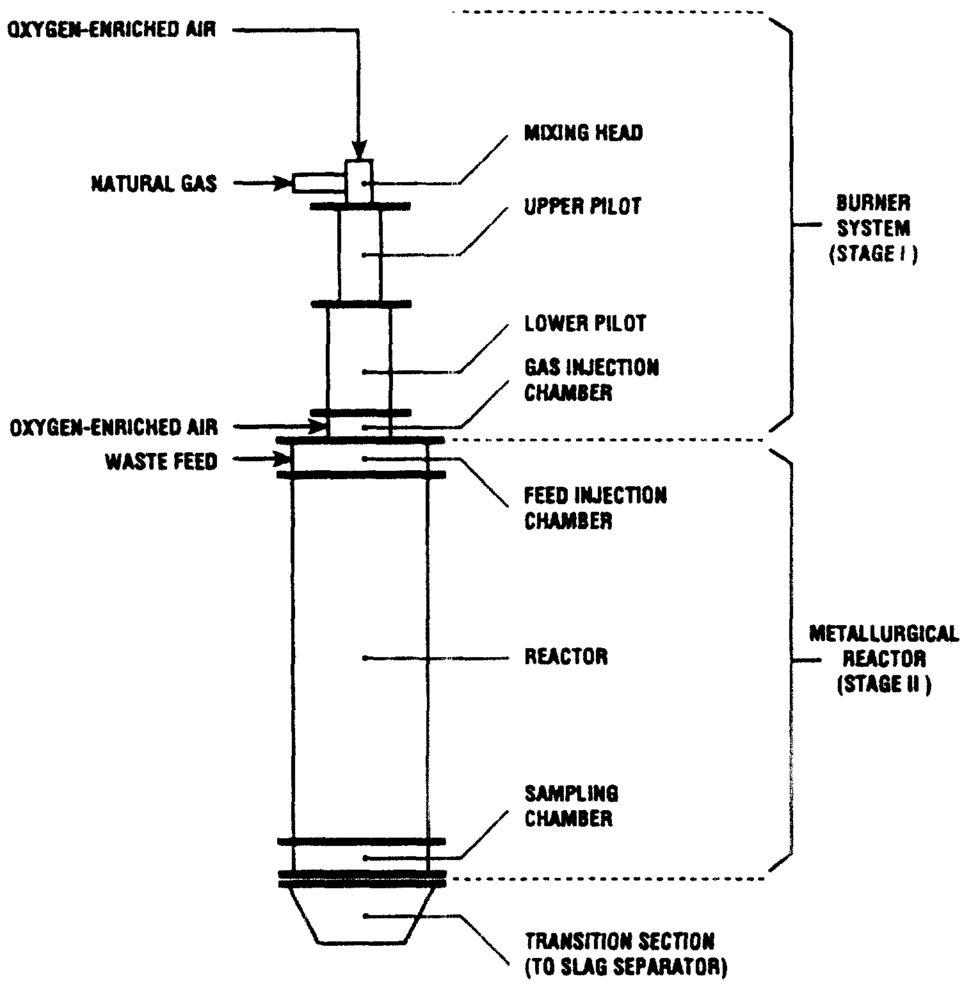
Combustion of natural gas (CH4)

$$CH_4 + 3/2O_2 \rightarrow CO + 2H_2O$$
$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
$$CH_4 + CO_2 + O_2 \rightarrow 2CO + 2H_2O$$
$$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$$

Reduction/Smelting of Volatile Metals

Iron:	$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$
Zinc:	$ZnO + CO \rightarrow Zn\ (vapor) + CO_2$
Cadmium:	$CdO + CO \rightarrow Cd\ (vapor) + CO_2$
Zinc-Iron:	$ZnFe_2O_4 + 2CO \rightarrow Zn\ (vapor) + 2FeO + 2CO_2$
Lead:	$PbSO_4 + 2CO \rightarrow Pb\ (vapor) + SO_2 + 2CO_2$
Lead:	$PbSO_4 + CO \rightarrow PbO + SO_2 + CO_2$

The nonvolatile components of the waste feed fuse, forming the effluent slag.



SOURCE: Horsehead Development Company, Inc.

Figure A-2. HRD Flame Reactor.

The energy required for fusion and reduction lowers the temperature to between 1,500°C and 1,700°C. At this temperature, several elemental metals are above their boiling point (see Table A-1) and volatilize into the gas stream with the O_2 and CO_2. Recovery of cadmium, lead, and zinc is of particular interest because of their economic value.

The reactor vessel is water-cooled to assure that a layer of the molten slag solidifies on the inner reactor walls. The slag layer protects the reactor walls from intense heat and reduces the reactor heat losses. Molten material is conveyed down the reactor walls by gravity and by the combustion gases. At the end of the reactor, the molten metal is accelerated through a tapered transition section into the horizontal slag separator.

A.4 Slag Separator

The reactor continuously discharges material into a refractory-lined, water-cooled cyclonic separator that separates molten slag from reactor off-gases. Off-gases contain mainly CO, hydrogen (H_2), and any metal vapors recovered from the waste feed. The effluent slag contains 35 to 75 percent of the mass of metals from the waste feed.

The slag separator is positioned horizontally between the flame reactor and the combustion chamber (see Figure A-1). The gases, particulate, and metal vapors flow toward the combustion chamber, countercurrent to the slag. The molten slag runs out through a tap hole on the discharge end of the unit. Occasionally a small amount of effluent slag is carried-over to the combustion chamber.

A.5 Combustion Chamber

The slag-free reactor off-gases are combusted again with air in a refractory-lined combustion chamber. The metal vapors oxidize and condense as solids, while combustible gases such as CO and H_2 are burned. The gas stream from the combustion chamber includes metallic oxides, CO_2, water

Table A-1. Boiling Points of Metals and Compounds of Interest

Metal	Boiling Point (°C)
Aluminum	2,407
Antimony	1,380
Arsenic	613
Barium	1,640
Cadmium	765
Calcium	1,490
Chromium	2,672
Copper	2,600
Iron	2,750
Lead	1,740
Magnesium	1,110
Mercury	357
Nickel	2,730
Potassium	774
Selenium	685
Silver	2,212
Sodium	883
Thallium	1457
Tin	2,260
Zinc	907

Source: CRC Handbook of Chemistry and Physics. 72nd Edition, 1991-1992

(H_2O), sulfur trioxide (SO_3), and NO_x. For the SITE demonstration, the temperature of the off-gases after the combustion chamber was typically between 700 and 1,000°C. Reactions in the combustion chamber include:

$$CO + 1/2O_2 \rightarrow CO_2$$
$$H_2 + 1/2O_2 \rightarrow H_2O$$
$$\text{Metal (vapor)} + 1/2O_2 \rightarrow \text{MetalO}$$
$$SO_2 + 1/2O_2 \rightarrow SO_3$$
$$\text{MetalO} + SO_3 \rightarrow \text{MetalSO}_4$$
$$N_2 + xO_2 \rightarrow 2NO_x$$

A.6 Oxide Product Recovery System

The oxide product (MetalO) recovery system is designed to cool the gas stream and capture the metal oxides formed in the combustion chamber. The system consists of a heat exchanger, a damper, and a baghouse for dust collection. An induced draft fan, located between the baghouse and the stack, provides the power for the system.

The gas is cooled by a shell-and-tube heat exchanger and by the addition of ambient air. The heat exchanger has water on the shell side and hot gases on the tube side. Because of the typically high particulate level in the gas stream, the heat exchanger tubes require frequent cleaning. The addition of ambient air is controlled by a damper. The damper is located just before the baghouse and is used to maintain the baghouse temperature below 200°C.

The dust collection system is a jet-pulsed baghouse designed to recover metal oxide product from the gas stream. The collection system emits off-gases through the plant stack and discharges metal oxide product into enclosed bulk storage bags for recovery. A rotary air lock, screw conveyors, and a sealed boot connection reduce the possibility of fugitive emissions. The baghouse collects the oxide product dust on 8,900 square feet of cloth.

The bag cleaning procedure consists of short, high-pressure pulses of air through the bags to dislodge the particles trapped on the surface. The pulses are initiated on a timed cycle based on typical gas flow rates and dust loadings. The particles fall by gravity into a screw conveyor below the bags. The screw conveyor moves the particles to an oxide product collection system composed of two bulk storage bags. While one storage bag is filling, the other can be removed and replaced with an empty storage bag.

The oxide product from the baghouse contains approximately 25 to 65 percent of the mass of the waste feed. Specific recoveries for volatile metals are generally very high. Based on past testing, the baghouse oxide product accounts for greater than 90 percent of the volatile metals in the waste feed. The remainder is encapsulated in the effluent slag, with a minimal fraction lost to the atmosphere as stack emissions.

References

CRC, 1991, CRC Handbook of Chemistry and Physics, Chemical Rubber Company, 72nd Edition, 1991-1992.

Appendix B
Vendor's Claims for the Technology

Appendix B
Vendor's Claims for the Technology

Note: This appendix to EPA's Applications Analysis Report was prepared by Horsehead Resource Development Company, Inc. Claims and interpretations of results in this Appendix are those made by the vendor and are not necessarily substantiated by test or cost data. Many of HRD's claims regarding cost and performance can be compared to the available data in Section 4 and Appendix C of the Applications Analysis Report.

B.1 Process Description

The Horsehead Resource Development Company, Inc. (HRD), Flame Reactor technology is an intense treatment process for metal-containing materials with proven capabilities for the following:

- Metal recovery and recycling
- Slag vitrification
- Organic chemical destruction

The technical and economic advantages of the Flame Reactor have been demonstrated in commercial-scale testing of a wide variety of metal-bearing materials at the HRD Flame Reactor demonstration plant in Monaca, Pennsylvania.

The HRD Flame Reactor Process employs a two-stage, high-temperature system to recover metals from wastes and residues. Carbonaceous fuel (pulverized coal or coke, or natural gas) is combusted with oxygen-enriched air under fuel-rich conditions in the first stage, or burner section. In the second stage, or reactor section, fine, dry feed is pneumatically injected into the hot (2,200 to 2,500°C) reducing flame. The intense process conditions allow short reaction times (less than 0.5 second) and permit a high waste throughput. Close control of the operating parameters and the reactor gas composition enables separation of valuable metals from the gangue components, as well as destruction of hazardous organic constituents.

The process temperature inside the reactor section is typically around 1,650°C, but may vary between 1,400 and 1,850°C. In the high-temperature reducing atmosphere, metals such as zinc, lead, arsenic, and cadmium are vaporized from the waste, along with volatile components such as alkali and halide compounds. Less volatile metals such as copper, nickel, and cobalt, if present in sufficient quantities, coalesce as a molten alloy. The remaining components of the waste, including some metal oxides (such as those of iron) melt into a molten effluent slag.

The reactor feeds directly into a slag separator, or horizontal cyclone, where the process gases and volatile compounds are separated from the molten materials. The effluent slag is continuously tapped and solidified on a noncontact, water-cooled, vibrating conveyor. The conveyor transports the effluent slag to a temporary collection bin, from there it is transferred to storage.

The process gases are drawn from the slag separator through the oxide product collection system, where the metal vapors are combusted again with ambient air and are condensed as metal oxides; all remaining hydrogen (H_2) and carbon monoxide (CO) are combusted to water vapor and carbon dioxide (CO_2). The gases are subsequently cooled, and the mixed metal oxide particulate is collected in a pulse-jet baghouse. A clean off-gas is discharged to the atmosphere.

Accurate metering of the fuel, combustion air, and feedstock maintains sufficient reducing conditions in the reactor. The reducing conditions in the reactor form metallic zinc, cadmium, and copper and leave iron as a reduced oxide. Controlling of the oxidation-reduction reactions offers several advantages. Volatile metals such as zinc and cadmium are readily extracted from the waste as metallic vapors, and condensable metals like copper can be separated from the molten slag as a molten alloy. Reducing iron to the oxide state, FeO, produces a more fluid and therefore more easily tapped slag than would otherwise be produced. Also, the metal alloys have a higher economic value without high levels of iron contamination.

For optimal Flame Reactor performance, the feed material should be very fine and contain little or no moisture. At a minimum, the feed characteristics should allow trouble-free pneumatic injection into the reactor. Moisture and particle size also affects reactor performance. As moisture or particle size increase, heat transfer rates and reaction rates are reduced.

The Flame Reactor processes waste most effectively and efficiently when 80 percent of the waste is less than 75 microns (200 mesh) and the total water content (including chemically bound water) is less than 5 percent. However, the

Flame Reactor has successfully processed material with only 80 percent of the waste feed less than 1,000 microns with 15 percent total water.

The Flame Reactor process does not require a minimum metal concentration in the feed for effective treatment. Even at very low metal concentrations, the Flame Reactor can render a material nonhazardous by immobilizing the metals in a vitrified effluent slag. However, in order for the metal oxide product to be sufficiently enriched for recycling, the total concentration of volatile metals, (such as cadmium, lead, and zinc) should be at least 5 percent. Likewise, condensable metals such as copper, nickel, and cobalt should total 5 percent or more in the feed in order to yield a molten metal alloy product.

The effluent slag produced during processing must be easily tapped from the slag separator. Therefore, the slag must be molten at 1,400 to 1,500°C and should have a viscosity of 2 Poise or less. If necessary, fluxing agents such as sand can be blended with the feed prior to processing.

B.2 Advantages of the Flame Reactor Process

HRD's Flame Reactor technology is uniquely suited to the recovery and recycling of metal contaminants from a variety of wastes and residues, and it is adaptable to different feed characteristics and remediation scenarios. This operating flexibility is possible because of the process thermodynamics, controlled metering of process inputs, and reliable analysis of process feed and product streams.

The extremely high processing temperature makes the Flame Reactor technology suitable for treatment applications involving the destruction of organic compounds and vitrification. However, the real strength of the technology is its ability to process waste containing metal constituents, which are then recovered in a concentrated form and can be recycled or sold to the secondary metals market. Because the HRD Flame Reactor recovers metals and destroys organic compounds, the technology is able to produce a nonhazardous product from a hazardous waste feed, eliminating hazardous waste liabilities.

The principal technical and economic advantages offered by HRD and the Flame Reactor technology are presented below.

1. The HRD Flame Reactor process recovers recyclable, metal-enriched products. The hazardous heavy metal components of the waste are separated into these metal products, eliminating hazardous waste generator liabilities. The value of the recyclable products typically offsets a portion of the processing costs.
2. The HRD Flame Reactor process produces a nonhazardous effluent slag. The effluent slag meets all Toxicity Characteristic Leaching Procedure (TCLP) regulatory requirements and can be used in various traditional aggregate applications.
3. Hazardous organic compounds are efficiently destroyed. Organic compounds are readily combusted in the high process temperatures, making the HRD Flame Reactor suitable for treating metal-bearing wastes that are also contaminated with hazardous organic chemicals.
4. HRD has experience in metal recovery and recycling. HRD is co-owned by Horsehead Industries, Inc., and Berzelius Umwelt-Service AG, a subsidiary of Metallgesellschaft AG of Germany; each have over a century of experience in the nonferrous metal industry.
5. The HRD Flame Reactor can be operated over a range of operating parameters. The possible range of operating conditions are presented in the table below. Because the HRD Flame Reactor is flexible over a wide range of parameters, operation can be tailored to treat specific feeds, optimizing process performance and economics.

<u>Range of Flame Reactor Operating Conditions</u>

Operating temperatures	1,350 to 1,850°C
Combustion air oxygen enrichment	50 to 80 percent
Waste feedrate	0.5 to 5 tons per hour
Plant capacity	5,000 to 60,000 tons per year
CO/CO_2 ratio	0.1 to 2.0

6. The HRD Flame Reactor can utilize a variety of fuels. Fuels successfully used in the HRD Flame Reactor include the following:
   - Natural gas
   - Liquefied natural gas
   - Low British thermal unit (Btu) coal
   - High Btu coal
   - Metallurgical coke fines
   - Petroleum coke
7. HRD Flame Reactor process applications can be expanded by using standard process technology. A variety of drying and size-reduction equipment may be added to the Flame Reactor to prepare wet or course waste feeds to optimal feed characteristics. Also scrubber technology can be added to the oxide product collection system to handle hydrogen chloride gas (HCl) and sulfur dioxide (SO_2) emissions generated during processing.
8. The HRD Flame Reactor process can meet environmental permit requirements. The Flame Reactor has met all permit regulations in commercial-scale testing at HRD's facility in Monaca, Pennsylvania. Commercial plant evaluations for a number of states, including Pennsylvania, Texas, and California have met with no permitting obstacles.
9. The HRD Flame Reactor process is amenable to modular construction. Modular construction is a low-cost option for permanent on-site construction at remote locations. Because of the possibility of modular

construction of the Flame Reactor, constructing a transportable plant is also feasible.

10. The HRD Flame Reactor has very short start-up and shutdown time. Most high-temperature operations require long start-up and shutdown periods, sometimes several days, in order to prevent temperature shock to critical components. Because the Flame Reactor has no refractory lining, the Flame Reactor can proceed from complete shutdown to waste processing in less than 15 minutes, and steady-state operations can be established within 30 minutes after start-up.

As stated above, the Flame Reactor can operate at temperatures in excess of 1,800°C, and burner flame temperatures of 2,700°C have been detected. The Flame Reactor burner can generate 25 to 30 million Btu per hour of energy and can produce over 200 cubic feet per minute of CO. For these reasons, the following precautions are employed to insure safe operation:

- Automatic shutdown if flame is extinguished
- Automatic shutdown due to high cooling-water temperature
- Automatic shutdown with loss of cooling-water pressure
- Automatic shutdown with loss of electrical power
- Automatic shutdown with loss of control air
- Nitrogen purge of the reactor
- Nitrogen purge in the baghouse

In addition, infrequent reactor water leaks do not result in steam explosions. The dynamics of the Flame Reactor are such that water entering the reactor is not trapped, but remains on the surface of the molten slag where it boils off.

B.3 Secondary Lead Smelter Soda Slag Test Program Summary

A summary of all of the Flame Reactor process test results on secondary lead smelter (SLS) soda slag is provided below. Additional information can be found in other sections of this report and in the Technical Evaluation Report for this Superfund Innovative Technology Evaluation (SITE) Demonstration.

Seventy-two tons of SLS slag, a residue from the National Smelting and Refining (NSR) soda slag lead battery recycling process, was obtained from a stockpile of approximately 350 tons in Atlanta, Georgia. The SLS slag was generated at a plant in Pedricktown, New Jersey, where a stockpile of 5,000 to 15,000 tons of SLS slag is located. Both the Atlanta and Pedricktown locations are Superfund sites.

When received, the SLS slag averaged about 9.7 percent moisture and was very coarse, as indicated by the particle size distribution (PSD) shown in Table B-1. Chunks of material larger than about 4 inches, some with diameters of over 2 feet, were excluded from the sample used for the data in Table B-1. Prior to Flame Reactor processing, the SLS slag was dried to between 2 and 7 percent moisture, and it was crushed in a hammermill to less than 3/16 inch diameter. Roughly 65 tons of dried and crushed waste feed were prepared from the initial 72 tons. The prepared material is characterized in Table B-2. The testing was performed in three phases: (1) a series of shakedown runs to determine the operating conditions for the demonstration test, (2) the EPA SITE demonstration test runs, and (3) a series of runs that added flux to the waste feed. These phases are summarized below, and each is reviewed in full or in part in other sections of this document and in the Technical Evaluation Report prepared for the HRD SITE Demonstration.

Table B-1. Particle Size Distribution of SLS Slag as Received

Mesh Size	Percent Passing
2 inch	64.8
1.5 inch	59.1
1 inch	54.0
0.625 inch	48.3
0.25 inch	39.2
0.111 inch	32.0

Table B-2. Characterization of Prepared Waste Feed

Analyte	Percent Weight
Lead - dry basis	7.01
Iron - dry basis	11.0
Sodium - dry basis	10.7
Silica - dry basis	2.68
Moisture (weight loss at 110°C)	5.2
Passing 60 mesh	50.9
Passing 100 mesh	36.4
Passing 200 mesh	22.9
Passing 325 mesh	15.2

X-ray diffraction indicated that the principal lead, iron, and sodium compounds were caracolite [$Na_3Pb_2(SO_4)_3Cl$], hydrous iron oxides, and sodium sulfate, respectively. Metallic iron, metallic lead, and carbon particles were also present as artifacts of the SLS slag process. Throughout the tests, the prepared SLS slag handled well in the Flame Reactor feed system.

B.3.1 Shakedown Runs

In a series of shakedown runs, 19.5 tons (roughly 30 percent) of the waste feed were treated over the range of process operating conditions summarized in Table B-3. The

Table B-3. Operating Parameters for Shakedown Runs

Parameter	Range
Feedrate, tons per hour	0.77 - 1.44
Natural gas, mcf per ton	14.9 - 26.3
Oxygen, 100 scf per ton	230 - 418
Combustion air, percent oxygen	59.7 - 85.1

Notes:
mcf = thousand cubic feet
scf = standard cubic feet

main objective of the shakedown runs was to identify the optimal operating conditions for the demonstration test; the tests also evaluated the response of Flame Reactor parameters to the material.

A summary of the results of the shakedown runs, including chemical analyses of the effluent slag and oxide product, is presented in Table B-4. TCLP results for several effluent slag samples appear in Table B-5 along with corresponding lead analyses.

Table B-4. Results of Shakedown Runs (Weight Percent)

Analyte	Concentration Range
Effluent Slag	
Lead	0.096 - 3.08
Iron	22.7 - 32.7
Sodium	12.0 - 14.8
Silicon	5.93 - 8.88
Sulfur	1.7 - 6.0
Oxide Product	
Lead	15.3 - 23.9
Iron	2.62 - 4.81
Sodium	9.08 - 15.4
Sulfur	9.7 - 16.4

Lead recovery to the oxide was high for all of the runs, and the Flame Reactor effluent slag was nonhazardous for a wide range of lead concentrations. The PSD of the prepared waste feed, though larger than recommended for Flame Reactor processing, did not obstruct treatment. However, unreacted particles of carbon and metallic iron were found in a microscopic examination of the effluent slag.

For all of the runs, the effluent slag was tapped from the separator and solidified on cooling into a solid mass on the water-cooled conveyor, but within a few hours, the effluent slag became friable and eventually broke down into a coarse powder. This disintegration was caused by a hydration reaction and occurred in all of the shakedown runs. The

Table B-5. TCLP Results from Shakedown Runs (milligrams per liter)

Analyte	Sample 1	Sample 2	Sample 3
Arsenic	<0.13	0.55	3.3
Barium	0.45	0.33	<0.10
Cadmium	<0.02	<0.02	<0.02
Chromium	<0.1	<0.1	<0.1
Lead	<0.2	<0.2	<0.2
Mercury	<0.1	0.1	<0.1
Selenium	<0.25	<0.25	<0.25
Silver	<0.01	<0.1	<0.1
Lead in Slag, Percent	0.20	0.99	1.93

effluent slag absorbed moisture from the air, and the recrystallization due to hydration caused the slag to break up. This disintegration occurred in a matter of minutes if the effluent slag was placed in water, but it did not if the slag was kept in a sealed container. A second reaction, observed in only a few runs, involved the formation of lead sulfate. In these cases, a white deposit was observed forming on the surface of the effluent slag after being tapped from the separator. This reaction also caused the cooled effluent slag to break up. The occurrence of lead sulfate was verified by minerallographic analysis.

B.3.2 Demonstration Test

The purpose of the demonstration test was to evaluate the Flame Reactor process as a viable candidate for hazardous waste treatment. The specific objectives are discussed elsewhere in this document. The work was done within the guidelines defined by the EPA SITE program with specific objectives established by the EPA SITE Project Managers.

A split of the samples taken by the EPA subcontractors during the demonstration tests were also analyzed by HRD. The carbon analyses were done on a Leco carbon analyzer, chloride was determined by Volhard titration, and fluoride analysis involved distillation and subsequent determination using a specific ion electrode. All other analyses were done by inductively coupled plasma spectroscopy (ICP) using a dissolution procedure modified from a U.S. Bureau of Mines method that uses a mixture of mineral acids to dissolve the entire sample. This method does not meet EPA QA/QC requirements.

For ICP analyses, EPA chose digestion by a modification of EPA Method 3050. EPA Method 3050 did not dissolve the entire sample. Therefore the sample size was reduced prior to sample digestion. EPA Method 3050 is also known to cause a low bias for silicon and chromium. The relative merits of the ICP dissolution methods used by HRD and EPA are discussed in considerable detail in the Technical Evaluation Report for this project. The averages of both sets of chemical analyses appear in Table B-6.

Table B-6. Average Composition of Solids as Analyzed by HRD and EPA (percent)

	Waste Feed		Effluent Slag		Oxide Product	
Analyte	EPA	HRD	EPA	HRD	EPA	HRD
Aluminum	0.60	0.69	1.53	1.64	0.062	0.080
Antimony	0.037	NA[a]	0.036	NA	0.12	NA
Arsenic	0.52	NA	0.026	NA	0.11	NA
Barium	0.086	NA	0.16	NA	0.028	NA
Beryllium	0.0001	NA	0.0001	NA	0.0001	NA
Cadmium	0.041	0.043	0.0004	<0.001	0.14	0.15
Calcium	0.65	0.72	1.30	1.57	0.23	0.21
Carbon	15.0	14.7	NA	1.09	NA	<0.1
Chloride	2.46	2.64	NA	0.37	NA	2.95
Chromium	0.0088	0.024	0.0089	0.040	0.031	0.034
Copper	0.19	0.17	0.34	0.37	0.17	0.19
Fluoride	0.013	0.031	NA	0.016	NA	0.033
Iron	10.3	10.8	20.5	22.7	3.18	4.12
Lead	5.41	6.10	0.55	1.12[b]	18.0	19.1
Magnesium	0.23	0.26	0.54	0.63	0.035	0.045
Manganese	0.075	0.074	0.18	0.18	0.028	0.32
Mercury	0.00007	NA	0.00001	NA	0.00001	NA
Potassium	0.24	0.23	0.24	0.27	0.74	0.74
Selenium	0.0073	NA	0.0034	NA	0.0066	NA
Silicon	0.28	8.10	0.33	10.2	0.11	10.5
Silver	0.0003	NA	0.0004	NA	0.0027	NA
Sodium	12.2	12.2	15.5	15.3	16.8	15.6
Sulfur	5.25	8.4	NA	5.6	NA	14.7
Thallium	0.025	NA	0.069	NA	0.0071	NA
Tin	0.28	NA	0.080	NA	0.69	NA
Zinc	0.42	0.44	0.16	0.12	1.62	2.19

Notes:

a NA = Not applicable

b A single effluent slag assay of 9.77 percent lead was excluded from this average since it is inconsistent with all other effluent slag analyses. The aberration is attributed to lack of homogeneity of the waste feed and the small sample size (several grams) sent to HRD. Inclusion of the assay raises the average to 1.60 percent lead.

Partitioning of the major elements into effluent slag and oxide product was calculated using a statistically based material balance program loaded on a personal computer. By evaluating the interrelation of the data and the quality of the data points, the material balance program calculates an internally consistent balance of the process streams and their components. Table B-7 presents the percent recoveries of selected elements in the oxide, which were determined using this material balance calculation.

Table B-7. Oxide Product Recovery Rates for The Demonstration Test (percent)

Analyte	Percent Recovery
Lead	87
Sodium	34
Sulfur	40
Iron	9
Silicon	35

The demonstration tests proved that the Flame Reactor can consistently treat SLS slag to produce a recyclable metal oxide product and a nonhazardous effluent slag. The

Table B-8. Average TCLP Results for Demonstration Test (milligrams per liter)

Analyte	Concentration
Arsenic	0.474
Barium	0.175
Cadmium	<0.050
Chromium	<0.060
Lead	<0.330
Mercury	<0.010
Selenium	0.033
Silver	<0.050

effluent slag consistently passed TCLP testing for leachable metals. The average TCLP results are listed in Table B-8.

B.3.3 Flux Additions

Silica flour flux (ground silica sand) was added to the waste feed to improve the physical characteristics of the effluent slag without diminishing the Flame Reactor's ability to detoxify the hazardous waste. The effluent slag from unfluxed processing, because it disintegrates when exposed to moisture, has no reuse value and must be disposed in a nonhazardous landfill. By adding flux to make a stronger slag, the effluent slag may be marketed in one or more aggregate applications, thereby reducing or eliminating the costs associated with disposal. This would also create zero waste from Flame Reactor treatment of SLS slag, because both the oxide product and the effluent slag can be recycled or reused.

The SLS slag was fluxed at levels of 12.5 percent and 25 percent. The fluxing rate is calculated by 100 percent times the ratio of flux to waste feed. A summary of the operating conditions for these runs appears in Table B-9, and the ranges of chemical analyses for the major slag constituents are presented in Table B-10.

At the 25 percent fluxing rate, the effluent slag did not disintegrate even when submerged in water. Somewhat glassy in appearance, this material might be used for such applications as a road base, an anti-skid material, or asphalt. At the 12.5 percent fluxing rate, the effluent slag disintegrated.

Table B-9. Operating Parameters Silica Flux Addition Runs

Parameter	12.5 Percent Silica	25 Percent Silica
Feedrate, tons per hour	0.63 - 0.83	0.68 - 1.2
Natural gas, mcf per ton	18.9 - 30.0	10.3 - 15.9
Oxygen, 100 scf per ton	248 - 482	211 - 358
Combustion air, Percent Oxygen	63.7 - 84.0	66.4 - 82.3

Note:

mcf = thousand cubic feet

Table B-10. Range of Analyses for Silica Flux Addition Runs (percent)

Analyte	12.5 Percent Silica	25 Percent Silica
Effluent Slag		
Lead	0.37 - 3.49	0.51 - 1.92
Iron	18.3 - 25.7	14.2 - 20.6
Sodium	14.1 - 21.2	10.9 - 12.9
Silicon	13.0 - 24.8	16.0 - 37.4
Oxide Product		
Lead	16.0 - 20.8	15.5 - 20.3
Iron	3.60 - 5.51	2.93 - 4.91
Sodium	14.0 - 16.1	9.17 - 14.1
Silicon	3.48 - 21.2	2.23 - 21.2
Sulfur	12.9 - 15.5	9.15 - 11.3

Table B-11 contains TCLP results for selected samples of effluent slag from the 12.5 percent and 25 percent flux rate runs. Table B-12 lists the percent recoveries of the principal

Table B-11. TCLP Results For Silica Flux Addition Runs (milligrams per liter)

Analyte	12.5 percent silica	25 percent silica
Arsenic	<0.13	<0.13
Barium	0.41	1.6
Cadmium	<0.02	0.13
Chromium	<0.10	<0.10
Lead	0.20	<0.20
Mercury	<0.10	<0.10
Selenium	<0.25	<0.25
Silver	<0.01	<0.01

Table B-12. Percent Recovery Rates for Metals in Oxide Product for Silica Flux Addition Runs (percent)

Analyte	12.5 Percent Silica	25 Percent Silica
Lead	93 - 96	87 - 97
Sodium	40 - 50	42 - 51
Sulfur	46 - 57	41 - 44
Iron	11 - 17	12 - 17
Silicon	24 - 33[a]	12 - 35[a]

Note:

[a] The higher fraction of silicon in the oxide is a result of carry-over of the fine silica flour to the baghouse.

elements in the products. The recoveries are based on the combined mass flow of the waste feed and flux and were calculated using a statistically based material balance program loaded on a personal computer.

TCLP results are consistent with the unfluxed SLS slag data and demonstrate that the Flame Reactor's ability to detoxicify the SLS slag was not impaired by the addition of silica flux. With the exception of silicon, the recoveries presented in Table B-12 are also in agreement with the unfluxed processing of SLS slag. The higher fraction of silicon in the oxide is a result of carry-over of the fine silica flour to the baghouse. This could be reduced by using a coarser silica as a fluxing agent.

B.4 Commercial Processing of Secondary Lead Smelter Slag

A preliminary operating cost estimate has been developed to process the remaining SLS slag stockpile located in Pedricktown, New Jersey, at the Monaca Flame Reactor facility. The estimate is based on the results of the SLS slag tests and the following assumptions:

- Processing would be performed at the Monaca Flame Reactor facility.
- Excavation, loading, and transportation costs to Monaca are not included.
- The SLS slag will be crushed to a PSD of 80 percent by weight less than 200 mesh and will be dried to less than 2 percent free moisture.
- A 25 percent addition of silica flux will be used to improve effluent slag integrity.
- The SLS slag will be fed at 2.7 tons per hour (tph) or about 3.4 tph with flux.
- The costs are presented on a $ per ton basis for processing 12,000 tons of material.
- Off-gas scrubbing for HCl or SO_2 is not required.

The estimated operating costs are summarized below in Table B-13. Pretreatment labor and utility costs are included with the Flame Reactor cost. Overall staffing, including supervision, will require twelve people. The pretreatment circuit may be run by a single operator two shifts per day, 5 days per week. The Flame Reactor will operate 24 hours per day, 7 days per week. Two Flame Reactor operators will be required for each of the four shifts, with one daylight mechanic and one supervisor.

Start-up and shutdown of the Flame Reactor and feed preparation circuit will require an estimated 3 days. A mechanic and supervisor will be required, bringing the total to 30 man-days.

Capital cost assume financing at 12 percent interest over 10 years. The effluent slag is assumed to be marketed at a value equivalent to handling and shipping costs for no net profit or loss.

Table B-13. Processing Fee for Flame Reactor Processing of SLS Slag

Cost Factors	Units	$/Unit	Units/ton	Cost/ton
Natural Gas	mcf	3.50	8.62	30.15
Oxygen	100 scf	0.25	189.3	47.31
Labor	Manhours	20.00	1.41	28.16
Electricity	kilowatthour	0.05	305.0	15.25
Flux	tons	36.00	0.25	9.00
Materials and Supplies				17.28
Direct Costs (subtotal)				147.15
Indirect Costs				10.00
Capital and Taxes				58.06
Subtotal				215.21
Oxide Product Shipping and Recycling				0.00
Effluent Slag Handling and Marketing				0.00
NET PROCESSING FEE				$215.21

References

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J. F. Pusateri and others, 1988, Apparatus for the Pyrometallurgical Treatment of Finely Divided Materials, U.S. Patent 4,732,368 (March 22).

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Appendix C
HRD Flame Reactor Site Demonstration Test Results

Appendix C
HRD Flame Reactor Site Demonstration Test Results

This Appendix presents a summary of the Horsehead Resource Development Company (HRD) Flame Reactor SITE demonstration. A detailed presentation of the SITE demonstration results can be found in the Technical Evaluation Report. The SITE demonstration was conducted at HRD's research facility in Monaca, Pennsylvania, 35 miles northwest of Pittsburgh, using secondary lead smelter (SLS) soda slag waste feed from the National Smelting and Refining (NSR) site in Atlanta, Georgia. The waste was transported to HRD, pretreated, and processed. The residuals resulting from processing included a nonhazardous effluent slag and a metal oxide product.

C.1 The NSR Site

The waste treated during the HRD SITE demonstration was transported to HRD from the NSR site. The NSR site is located at 430 Bishop Street in the northwest portion of Atlanta, Georgia, in an industrialized area that is intermixed with residential communities. Approximately 1 acre of the 4-acre site is owned by the Southern Railroad Company (which is owned by Norfolk Southern Corporation), and the remaining 3 acres are owned by Atlanta Forge and Foundry Company. The waste treated is located on the property belonging to Atlanta Forge and Foundry Company (NL Industries, 1989 and 1990).

The facility has been operated by various owners for approximately 80 years. During a portion of this time, lead smelting and refining activities were performed at the site. The most recent operations at the facility involved the recovery of lead from storage batteries and other lead-bearing scrap and secondary lead smelting activities. NSR purchased the facility from NL Industries on June 30, 1981, and operated the facility until March 1984, at which time NSR filed for bankruptcy. Since 1984, the facility has been inactive (U.S. EPA, 1989; NL Industries, 1990).

During the 3 years that NSR operated the facility, approximately 350 tons of processed rotary-kiln SLS slag from the NL Industries' Superfund site in Pedricktown, New Jersey, were shipped to the NSR facility in Atlanta for possible recycling. This waste material was stored in two bunkers at the NSR site. Seventy-two tons of this material were collected, loaded in bulk storage bags in closed trailers, and manifested for shipment to the HRD facility for treatment during the demonstration.

C.2 The HRD Facility

The HRD Flame Reactor pilot plant is located near Monaca, Pennsylvania, and is operated by HRD, a division of Horsehead Industries, Inc. The HRD Flame Reactor plant and associated facilities occupy about 3 acres on a 5-acre site. The plant and facilities include the main building that houses the reactor; an auxiliary storage building; liquid oxygen (O_2) and nitrogen (N_2) storage facilities; an oxide product collection system with a bag-house oxide collector; a cooling tower for the closed-loop, noncontact cooling water system; and a pretreatment facility containing a waste feed dryer and a hammermill. The facility is presently operating under authority of an EPA RD&D permit (U.S. EPA I.D. No. PAD 98 111 0570) and a Pennsylvania Department of Environmental Resources (PaDER) hazardous waste storage and treatment permit for research testing of electric arc furnace (EAF) dust (RCRA code K061 hazardous waste), and certain characteristic wastes. These operating permits have allowed extensive testing of the HRD Flame Reactor.

The main HRD Flame Reactor building, measuring 40 by 80 feet and 60 feet high, presently contains the feed handling and storage equipment, the reactor and slag separator, the effluent slag cooling and conveying table, the control room connected to a computer in the main office building, and the motor control center. It also includes maintenance and spare parts storage. The cooling tower, baghouse, and liquid O_2 storage are located in the area outside the main reactor building. Adjacent to the Flame Reactor building is an office building housing administrative and engineering offices and the computer center.

C.3 Description of Operations

After arriving at the demonstration site at the HRD facility, SLS slag waste was stored in bulk storage bags in a covered storage facility adjacent to the HRD Flame Reactor building. The SLS slag was dried and crushed by feed preparation equipment, located in a separate building. The feed preparation equipment is designed to dry and crush the SLS slag with a dryer and a hammermill. Once the SLS slag was crushed and dried to the necessary specifications (see Section 3 of this report), it was then loaded into portable bins and transported to the storage facility prior to processing, as waste feed, in the HRD Flame Reactor.

Startup testing of the demonstration equipment began after the feed preparation equipment had processed a sufficient quantity of SLS slag to produce 5 to 10 tons of dry, crushed waste feed. Prior to initial system startup, EPA and the SITE team contractor reviewed the Demonstration Plan for the HRD Flame Reactor (U.S. EPA, 1990) with HRD personnel. During startup, the HRD Flame Reactor system was checked for any problems that would prevent smooth operation of the equipment. No problems were identified.

The next phase was the shakedown period. A thermochemical process model was used to calculate operating set points for feed rate, reactor temperature, O_2 combustion air content, and other operating parameters. The set points were then adjusted during the shakedown runs by monitoring reactor conditions and evaluating the condition of the effluent slag generated. The production of a free-flowing, low-lead effluent slag indicated that the proper values for the set points had been attained. The actual demonstration was performed with the values set during the shakedown runs.

The SITE demonstration took place the week of March 17, 1991, approximately 4 weeks after the startup procedures and shakedown were completed. The initial run was a background or blank run to establish a process baseline. During the blank run, only natural gas was fired in the reactor; no waste feed was admitted to the system. Stack gas emissions were monitored and gas samples were collected during the blank run.

Waste feed processing began after blank testing was completed. During the waste feed runs, samples were collected at various process points. These samples included waste feed, oxide product, effluent slag, and stack gas emissions. The number of samples collected at each location, the frequency, and the rationale for sampling and analysis parameters are discussed in Section 3.4 of the Demonstration Plan for the HRD Flame Reactor (U.S. EPA, 1990), as well as in the Technology Evaluation Report for this technology (U.S. EPA, 1992). Samples of the waste feed, oxide product, and effluent slag were taken every 15 minutes. Six hourly composites, consisting of four subsamples each, were collected during each run for the waste feed and effluent slag. One daily composite of all the subsamples of the oxide product was collected for each run. Stack gas emissions were continuously monitored during the entire run, and stack samples were collected for 2-1/2 hours during the middle of each test run.

Four waste feed test runs (Runs 1, 2, 3, and 4) were conducted during this phase of the demonstration on 4 consecutive days. The first run was discarded due to fluctuations in the stack gas temperature, pressure, and flow rate.

C.4 Analytical Results and Discussion

This section discusses the analytical results of the HRD SITE demonstration. First, the results of the Toxicity Characteristic Leaching Procedure (TCLP) tests are discussed to determine if a nonhazardous effluent slag was produced. Second, the constituent analysis results are presented. The main purpose of the constituent analysis data is to determine if the technology produced a recyclable metal oxide product enriched in lead. Mass balance during the treatment process, including factors affecting weight reduction and percent recovery are also discussed. In addition, constituent analysis data is used to characterize the waste feed stream, and the results of stack monitoring and emission sampling will be discussed. A complete presentation of the analytical results is presented in the HRD Technology Evaluation Report (U.S. EPA, 1992).

C.4.1 TCLP Results

TCLP tests were performed on the waste feed and on the effluent slag. Table C-1 presents the mean values, ranges, and standard deviations of the results as well as the appropriate RCRA regulatory criteria. As expected, the waste feed was a RCRA characteristic waste because of cadmium (D006) and lead (D008) concentrations. TCLP testing determined that the effluent slag was not a characteristic waste. In fact, the levels of cadmium, chromium, and lead were all reduced to values below their respective laboratory detection limits, and the level of selenium was reduced by half. The levels of arsenic and barium both increased, though they are still well below the RCRA regulatory limit.

C.4.2 Constituent Analysis

Constituent analysis was performed on the waste feed, oxide product, and effluent slag in order to determine if the technology produced a recyclable oxide product enriched in lead and an effluent slag product with lowered lead concentration.

Two analytical digestion methods for metals were used. The preferred digestion method was EPA Method 3050, because it is a validated method with a standard operating procedure that can be followed by any laboratory. The other method was the method HRD uses, which is a mineral acid procedure with microwave heating. All constituent analysis results reported below are mean values obtained by using a slightly modified EPA Method 3050 digestion procedure which used a reduced sample size, unless otherwise noted.

The waste feed and the effluent slag matrices are both difficult to digest and nonhomogeneous. The modified EPA Method 3050 digestion procedure produces low concentrations for silicon and chromium (less that 20 percent of the results of the HRD digestion procedure). The silicon and chromium analyses were not considered to be of major concern in this demonstration. Therefore, in discussions below but not in the data tables, HRD silicon and chromium data is reported. The HRD method is not validated by EPA. The lack of homogeneity of the matrix was demonstrated by poor duplicate results and by the large standard deviations relative to each mean. A complete tabulation of HRD SITE demonstration results is presented

Table C-1. TCLP Results for the Waste Feed and Effluent Slag (mg/l)

	Extract Concentration			
	Mean[a]	Range	Standard Deviation	RCRA Limit
Waste Feed				
Arsenic	0.213	<0.210-0.264	0.012	5.0
Barium	0.0347	0.0177-0.0675	0.014	100.0
Cadmium	12.8	7.61-15.8	2.63	1.0
Chromium	0.184	0.140-0.283	0.033	5.0
Lead	5.75	4.35-6.80	0.705	5.0
Mercury	<0.010	<0.010	NA	0.2
Selenium	0.0716	<0.030-0.160	0.048	1.0
Silver	<0.050	<0.050	NA	5.0
Effluent Slag				
Arsenic	0.474	<0.210-0.930	0.188	5.0
Barium	0.175	0.109-0.281	0.042	100.0
Cadmium	<0.050	<0.050	NA	1.0
Chromium	<0.060	<0.060	NA	5.0
Lead	<0.330	<0.330	NA	5.0
Mercury	<0.010	<0.010	NA	0.2
Selenium	0.0326	<0.030-0.730	0.010	1.0
Silver	<0.050	<0.050	NA	5.0

Notes:

[a] Average of 18 values; when an analyte was present below the detection limit, the detection limit was used in calculations.

NA = Not applicable

mg/L = milligrams per liter

in the HRD Technology Evaluation Report (U.S. EPA, 1992).

Tables C-2 and C-3 present the constituent analysis data for the waste feed and the oxide product, respectively. The data show clearly that volatile metals (lead, cadmium, and zinc) are concentrated in the oxide product, while nonvolatile metals (aluminum, calcium, iron) are concentrated in the effluent slag. The oxide product contains some nonvolatile species, because some effluent slag particles are entrained with the off-gas stream.

Table C-4 presents constituent analysis data for the effluent slag. The main constituents of the effluent slag are iron (20.4 percent), sodium (15.5 percent), calcium (1.30 percent), and aluminum (1.53 percent). Silicon is reported by HRD to be present in the effluent slag at an average concentration of 10.2 percent. In general, the effluent slag is composed of the oxides of nonvolatile metals such as iron, calcium, and aluminum. Silicon and sodium appear in both the oxide product and the effluent slag.

C.4.3 Mass Balance

A mass balance was performed on the HRD Flame Reactor process using materials inventory data (total waste feed, oxide product, and effluent slag) and the metals concentration data for all three streams. Mass balance is an accounting of where chemicals in the waste feed are partitioned in the products after processing. Mass balance closure is a determination of the amount of each chemical present in the waste feed which can be accounted for in the products. Stack emissions are not included because they are small in relation to the other streams. For example, lead, the largest stack emission, totaled 0.2 pounds compared to approximately 2,000 pounds of lead in the oxide product for the entire demonstration.

C.4.4 Weight Reduction

For all four test runs, a total of 47,300 pounds of waste feed were processed, generating 11,200 pounds of oxide product and 15,300 pounds of effluent slag. The total mass of oxide product and effluent slag only account for 56.1 percent of the waste feed mass. Therefore, the process has a net weight

Table C-2. Waste Feed Analyses (weight percent)

Analyte	Mean[a]	Standard Deviation	Range
Aluminum	0.596	0.0800	0.490-0.787
Antimony	0.0373	0.00503	0.0278-0.0455
Arsenic	0.0515	0.0132	0.0428-0.104
Barium	0.0861	0.00312	0.0804-0.0940
Beryllium	<0.00011	NA	<0.00011
Cadmium	0.0411	0.00345	0.0356-0.0512
Calcium	0.653	0.0702	0.552-0.835
Chromium[b]	0.00877	0.00148	0.00631-0.0113
Copper	0.185	0.0239	0.146-0.259
Iron	10.3	0.753	9.56-13.0
Lead	5.41	0.414	4.82-6.17
Magnesium	0.228	0.0559	0.163-0.346
Manganese	0.0753	0.00706	0.0672-0.0903
Mercury	0.000068	0.000010	0.000054-0.000087
Potassium	0.244	0.0255	0.204-0.284
Selenium	0.00727	0.00290	0.00400-0.0175
Silicon[b]	0.276	0.0716	0.176-0.444
Silver	0.000339	0.000096	0.000180-0.000540
Sodium	12.2	0.478	11.5-13.2
Thallium	0.0253	0.00424	0.0181-0.0317
Tin	0.282	0.0129	0.261-0.314
Zinc	0.416	0.0744	0.321-0.681

Notes:

a Average of 18 hourly composites, six each from Runs 2, 3, and 4 analyzed after pretreatment.

b Due to matrix interferences, analytical results are known to be lower than actual concentrations.

NA = Not applicable

reduction of 43.9 percent. After the demonstration was complete, a total of 3,460 pounds of treated waste was cleaned out of the combustion chamber and heat exchanger. This is 7.3 percent of the total waste feed processed. Therefore, if the clean out material is included, the weight reduction is 36.6 percent.

The main reasons for the weight reduction were the essentially complete conversion of carbon to carbon dioxide (CO_2) (15.0 percent), moisture to steam (3.35 percent), and chloride to hydrogen chloride (HCl) gas (2.46 percent). In addition, sulfur was partially converted to sulfur dioxide (SO_2) (2.26 percent). The remaining sulfur (2.99 percent) was trapped in either the oxide product or the effluent slag. These values are the average of data from Runs 2, 3, and 4.

The remaining 13.5 percent weight reduction is partially attributed to the complex chemistry of the reducing conditions in the HRD Flame Reactor. Oxygenated compounds in the waste feed reacted with carbon monoxide (CO) from the fuel to form metal vapors and CO_2, resulting in a loss of oxygen from various metal oxides. (Detailed reactions are presented in Appendix A of this report.) Some weight loss is also due to build up of material in the combustion chamber and heat exchanger and possibly due to measurement variations.

Table C-3. Oxide Product Analyses (weight percent)

Analyte	Mean[a]	Standard Deviation	Range
Aluminum	0.0562	0.00734	0.0459-0.0623
Antimony	0.125	0.00403	0.122-0.131
Arsenic	0.110	0.00680	0.101-0.117
Barium	0.0282	0.00310	0.0248-0.0323
Beryllium	<0.0001	NA	<0.0001
Cadmium	0.128	0.0139	0.108-0.138
Calcium	0.202	0.0343	0.155-0.234
Chromium[b]	0.0300	0.00154	0.0278-0.0313
Copper	0.161	0.0168	0.138-0.178
Iron	3.22	0.267	2.91-3.56
Lead	17.4	1.10	15.9-18.4
Magnesium	0.0327	0.00441	0.0266-0.0368
Manganese	0.0265	0.00370	0.0214-0.0300
Mercury	0.000013	0.000002	<0.000010-0.00014
Potassium	0.707	0.0548	0.630-0.751
Selenium	0.00520	0.00102	0.00415-0.00659
Silicon[b]	0.127	0.0102	0.113-0.137
Silver	0.00269	0.000622	0.00190-0.00342
Sodium	15.7	1.40	13.7-16.8
Thallium	0.00746	0.000243	0.00714-0.00773
Tin	0.660	0.0342	0.612-0.687
Zinc	1.38	0.272	1.00-1.62

Notes:

a Average of three composite samples from Runs 2, 3, and 4; when an analyte was present below the detection limit, the detection limit was used to calculate the average.

b Due to matrix interferences, analytical results are known to be lower than actual concentrations.

NA = Not applicable

Table C-4. Effluent Slag Analyses (weight percent)

Analyte	Mean[a]	Standard Deviation	Range
Aluminum	1.53	0.138	1.33-1.85
Antimony	0.0357	0.0412	0.0100-0.190
Arsenic	0.0262	0.0291	0.00921-0.134
Barium	0.165	0.0136	0.139-0.183
Beryllium	0.000101	0.000008	<0.00087-0.000110
Cadmium	0.000373	0.000254	<0.00023-0.00135
Calcium	1.30	0.0973	1.06-1.45
Chromium[b]	0.00890	0.00786	0.00339-0.0385
Copper	0.344	0.0324	0.273-0.389
Iron	20.4	1.60	16.7-22.8
Lead	0.552	0.252	0.156-1.14
Magnesium	0.543	0.0847	0.441-0.761
Manganese	0.175	0.0268	0.132-0.231
Mercury	<0.000010	NA	<0.000010
Potassium	0.238	0.0194	0.199-0.269
Selenium	0.00344	0.00345	<0.00226-0.0176
Silicon[b]	0.327	0.0979	0.183-0.525
Silver	0.000394	0.000082	0.000250-0.000510
Sodium	15.5	1.06	12.8-16.8
Thallium	0.0689	0.00862	0.0535-0.0852
Tin	0.0796	0.0150	0.0544-0.111
Zinc	0.113	0.0287	0.07109-0.168

Notes:

a Average of 18 hourly composites, six each from Runs 2, 3, and 4; when an analyte was present below the detection limit, the detection limit was used to calculate the average.

b Due to matrix interferences, analytical results are known to be lower than actual concentrations.

NA = Not applicable

C.4.5 Percent Recovery

Because no metals concentration data are available for Run 1, only data from Runs 2, 3, and 4 were used. The materials inventory data for these runs include: 32,600 pounds of waste feed, 7,860 pounds of oxide product, and 11,000 pounds of effluent slag. Table C-5 presents oxide product percent recovery data in two forms. The first form is the raw percent recovery when the oxide product is compared to the feed. Because mass balance closure is less than 100 percent, due mainly to build up of material in the combustion chamber and heat exchanger, the percent recoveries are low. For lead, zinc, and cadmium, the percent recoveries are 77.7, 80.0, and 75.0, respectively. The second method presents a normalized percent recovery. This method scales the percent recovery data based on the mass balance closure, so that the sum of the oxide product percent recovery and effluent slag percent recovery is 100 percent. Using this method, the percent recoveries of lead, zinc, and cadmium are 95.8, 89.7, and 99.6, respectively. EPA and HRD have no fully satisfactory explanation for the relatively low recoveries of arsenic, barium, or thallium in the oxide product. These metals do not behave as one would expect based solely on their boiling points. Arsenic is very volatile. Barium and thallium are less volatile, having boiling points similar to that of lead. The presence of metal species such as oxides or chlorides may explain the anomalous recoveries. The recoveries of these volatile metals warrant further study, which is outside the scope of this report.

One objective of this SITE Demonstration was to form a recyclable metal oxide product enriched in lead and zinc. The Flame Reactor was successfully optimized by HRD to do this. Arsenic and barium - and possibly thallium - have negative economic impact on oxide product recycling and were not desired in this product. Table C-6 presents the mass of cadmium, lead, and zinc, as well as the other major metals in the waste feed, oxide product, and effluent slag.

C.5 Feed Characterization

The analyses used to characterize the waste feed included determination of particle size distribution (PSD), moisture content, total carbon, energy content in British thermal units (Btu), ash content, chloride concentration, fluoride concentration, and sulfur concentration.

Analysis of PSD determined that 66.6 percent of the waste feed was smaller than 200 mesh. The complete distribution is shown in Table C-7. The standard deviation shows that the PSD for all the runs was fairly consistent. HRD recommends that 80 percent of the feed be less than 200 mesh (0.0029 inches) for optimal recovery of volatile metals.

The SLS slag transported from the NSR site had a moisture content of up to 30 percent. After pretreatment, the average total moisture content was reduced to 3.35 percent. The recommended moisture content is less than 5 percent total moisture.

Both total carbon and total organic carbon analyses were performed. These analyses produced results, within analytical limits, indicating that all of the carbon is organic carbon. The average total carbon content of the waste feed was 15.0 percent. The carbon in the waste feed is consumed as a fuel. The typical feed to the HRD Flame Reactor is low in carbon, but carbon content is not a feed characteristic that affects the recovery of volatile metals.

The average energy content of the waste feed was 1,665 Btu per pound (Btu/lb). This can be attributed to the 15 percent carbon present in the waste feed. A poor grade of

Table C-5. Mass Balance Closure and Percent Recovery for Metals Present in the Waste Feed

Analyte	Percent Mass Balance Closure	Oxide Product Percent Recovery[a]	Normalized Oxide Product Percent Recovery[b]
Aluminum	88.9	2.27	2.56
Calcium	74.5	7.48	10.0
Copper	83.5	21.0	25.1
Iron	74.6	7.53	10.1
Lead	81.2	77.7	95.8
Magnesium	83.5	8.50	9.77
Potassium	103	69.8	68.0
Silicon[c]	73.6	31.2	42.3
Sodium	73.5	30.9	42.0
Tin	66.1	56.6	85.6
Zinc	89.2	80.0	89.7

Notes:

a The percent of the metal in the effluent slag is the mass balance closure minus the oxide product recovery.
b The percent of the metal in the effluent slag is 100 minus the normalized oxide product percent recovery.
c Concentrations of silicon from HRD's analytical procedure were used.

Table C-6. Major Metal Flow Rates (pounds of metal)

Major Metals[a]	Feed[b]	Slag[b]	Oxide[b]
Aluminum	194	168	4.42
Antimony	12.1	3.93	9.84
Arsenic	16.8	2.87	8.67
Barium	28.0	18.1	2.22
Cadmium	13.4	0.0409	10.0
Calcium	213	143	15.9
Copper	60.4	37.8	12.6
Iron	3350	2250	253
Lead	1760	60.6	1370
Magnesium	74.4	59.6	2.57
Manganese	24.5	19.2	2.08
Potassium	79.6	26.2	55.6
Silicon[b]	89.8	35.8	10.0
Sodium	3980	1700	1230
Tin	91.7	8.74	51.9
Zinc	135	12.4	108

Notes:

a Major metals are defined as being present in the waste feed, oxide product, or effluent slag at a concentration greater than 0.1 percent.
b It is thought that the mass balance closure is less than 100 percent primarily because of build up of material in the system.

bituminous coal has a heating value of 11,420 Btu/lb (Perry, 1985).

The waste feed was, on average, 81.6 percent ash. This is not surprising given the fact that SLS slag is a residue from a high-temperature process. The remaining 18.4 percent of the SLS slag is almost entirely carbon (15.0 percent) and free moisture (3.35 percent).

The waste feed was analyzed for three additional chemical constituents: chloride, fluoride, and sulfur. The waste feed averaged 2.46 percent chloride by weight, 0.0130 percent fluoride by weight, and 5.25 percent sulfur by weight.

C.6 Stack Monitoring and Emissions Sampling

During the HRD Flame Reactor SITE Demonstration, stack gases were sampled for metals, HCl, and particulate emissions, and were continuously monitored for SO_2, nitrogen oxides (NO_x), O_2, CO_2, CO, and total hydrocarbons (THC). The metals and particulate emissions were determined using an EPA Modified Method 5, isokinetic, multiple metals sampling train. HCl emissions were determined by a single point EPA Method 26 sampling train. The continuous emission monitors used the following: EPA Method 6C for SO_2, EPA Method 7E for NO_x, EPA Method 3A for O_2 and CO_2, EPA Method 10 for CO, and EPA Method 25A for THC. All the standard EPA methods can be found in 40 CFR 60, Appendix A, and the multiple metals train is discussed in the Methods Manual for Compliance with the Boiler and Industrial Furnace (BIF) Regulations [40 CFR 266, Appendix IX].

Table C-7. Particle Size Distribution of Waste Feed as Percent by Weight

Mesh Size	Sieve Opening (Microns)	Mean[a] (Percent by weight)	Standard Deviation	Range
30 < x	600	7.92	1.01	5.74-9.69
60 < x < 30	250	8.74	0.693	7.34-10.1
100 < x < 60	150	7.53	0.694	6.40-9.25
200 < x < 100	75	9.16	0.897	7.25-11.0
325 < x < 200	45	2.29	0.308	1.87-3.04
x < 325	<45	64.3	1.54	61.6-67.8

Notes:

a Average of 18 values, six each from Runs 2, 3, and 4.

C.6.1 Metal Emissions

The metals emissions in the stack gas were calculated from the EPA Modified Method 5 sampling train data. The Modified Method 5 sampling train collects two types of samples. The first type, or "front half," is solid matter collected on a filter. The second type, or "back half," collects gaseous emissions by absorbing them in an acid solution. The analytical results, shown in Table C-8, are the sum of both halves. Table C-8 presents the metals emission rates for the blank run and the three valid test runs (Runs 2, 3, and 4), as well as the BIF Rule Tier II screening limits. The Tier II screening limits are presented for comparison only. EPA believes that most facilities will choose to comply with the less restrictive Tier III limits. Tier III limits are not presented because they involve site-specific dispersion modeling and risk analysis.

The HRD Flame Reactor emitted lead, chromium, and arsenic at rates above the Tier II screening limits during the SITE Demonstration; however, the detection limit for arsenic is too high for comparison to Tier II limits. The Tier II levels presented are restrictive because of the short stack and the complex terrain. (See Section 3.5 of the HRD Applications Analysis Report for a discussion of regulations.)

C.6.2 HCl Emissions

HCl emissions during the HRD Flame Reactor demonstration were between 38.5 and 46.4 pounds per hour

Table C-8. Metals Emission Rates of the HRD Flame Reactor (gram per hour)

Metal	Blank Run	Test Run 2	Test Run 3	Test Run 4	Tier II Screening Limits[a]	Above/ Below
Antimony	0.50[b]	0.39[c]	0.35[b,c]	0.37[b,c]	14	Below
Arsenic	0.39[b]	0.29[b]	0.27[b,c]	0.29[b,c]	0.11	Above
Barium	0.041	0.55	0.72	0.62	2400	Below
Beryllium	0.0067[b,c]	0.019[b,c]	0.018[b,c]	0.019[b,c]	0.20	Below
Cadmium	0.12[b]	0.24[b]	0.17[b]	0.17[b]	0.26	Below
Chromium	0.053[b]	1.0[b]	0.70[b]	1.0[b]	0.040	Above
Lead	12	12[b]	12[b]	12[b]	4.3	Above
Mercury	0.041[c]	1.1	1.3	0.96	14	Below
Silver	0.015	0.19	0.013[b,c]	0.014[b,c]	140	Below
Thallium	0.72[b,c]	2.3[b,c]	2.2[b,c]	2.3[b,c]	14	Below

Notes:

a Emission limits are based on emission of a single metal. Tier III standards based on site-specific dispersion modeling are less restrictive (see Section 3.5 of the HRD Applications Analysis Report).

b The concentration of this metal was below the analytical detection limit in the combined back half samples for this run.

c The concentration of this metal was below the analytical detection limit in the combined front half samples for this run.

(lb/hr). This high emission rate could be expected because the Flame Reactor had no acid gas control system, and the waste feed contained, on average, 2.46 percent chloride by weight. The BIF rule has promulgated risk-based emission limits on HCl. The Tier II screening limit is 0.091 g/sec (0.72 lb/hr) [56 FR 7232]. The addition of a wet scrubber should control HCl emissions to below the applicable standards.

C.6.3 Particulate Emissions

Because the HRD Flame Reactor process uses a baghouse to capture the metal oxide product, particulate emissions from the Flame Reactor are low when the baghouse is maintained and operated properly.

During analysis of the demonstration samples, problems occurred with the gravimetric analysis, preventing accurate determination of the particulate emissions for all but the blank run. Therefore, a worst case analysis of the test run particulate emissions was performed.

Particulate emissions are calculated from the sum of two gravimetric analyses. The first analysis is conducted on the filter. The EPA Method 5 sample train uses a filter that exhibits 99.95 percent efficiency on 0.3-micron dioctyl phthalate smoke. The filter is weighed before and after sampling. The resulting difference is equal to the particulate weight on the filter. The blank run and Run 3 were the only runs with positive differences. Negative numbers were replaced with 1 mg for a worst case analysis. The second gravimetric analysis is the acetone probe wash. The probe (that part of the EPA Method 5 train that carries the gas sample from the source to the filter) is rinsed with acetone to remove any particulate matter deposited on the probe. In the laboratory, the acetone is completely evaporated, and the residual is weighed. A laboratory error occurred, and thus residuals were weighed only to ±10 mg. The blank run and Run 2 were the only runs without negative numbers. For a worst case analysis, each run was assumed to show 10 mg of dried acetone residual.

Even under a worst case scenario, the test run particulate emissions were lower than the particulate emissions for the blank run. The blank run particulate emissions were slightly higher than runs containing waste, because no oxide product was formed to act as seed nuclei for particle formation and growth. Therefore, the particles formed were smaller and were not captured by the baghouse. The sources of the blank run particulate emissions may include residue material in the system and lime used to condition the baghouse bags.

The permit limit specified in the EPA RD&D permit for particulate emission is 0.02 grains per dry standard cubic foot (dscf). As shown in Table C-9, all particulate emissions were below this standard. Table C-9 also presents the particulate emissions in lb/hr and in grains/dscf corrected to 12 percent CO_2 and 7 percent O_2 for comparison purposes.

C.6.4 Continuous Emissions Monitoring Results

Emissions of SO_2, NO_x, O_2, CO_2, and THC were continuously monitored for the blank run and for each 6-hour test run. Table C-10 presents the average emission for each run.

The HRD Flame Reactor currently has an air quality permit issued by PaDER that limits SO_2 emissions to less than 500 parts per million (ppm) for commercial operations. For the SITE demonstration, for which the limit is not effective, the SO_2 emissions were below 500 ppm except for a 2-minute period during Run 2. The maximum SO_2 emission was 514 ppm, which occurred immediately following startup, after a system shut down was required to cool the oxide product collection systems.

Table C-9. Particulate Results

Test Run	mg/dscf	Grains/dscf	Grains/dscf Corrected to 12% CO2	7% O2	Pounds/hour
Blank	0.517	0.00797	0.0282	0.0786	0.522
2	0.191	0.00295	0.00887	0.0164	0.364
3	0.294	0.00454	0.0114	0.0233	0.548
4	0.213	0.00328	0.00894	0.0168	0.356

Notes

dscf = dry standard cubic feet
mg = milligrams

Table C-10. Results of Continuous Emission Monitoring

Gas	Units	Blank Run	Test Run 2	Test Run 3	Test Run 4
SO_2	ppm dry	ND	268	272	290
NO_x	ppm dry	173	16.0	15.81	18.5
O_2	percent	19.6	18.5	18.3	18.21
CO_2	percent	3.39	3.99	4.77	4.40
CO	ppm dry	4.17	ND	14.2[a]	1.28
THC	ppm dry as propane	1.64	1.61	1.7	0.91

Notes:

a The CO analyzer performed erratically during Test Run 3, therefore the CO data for that run are suspect.
ND = Not detected
ppm = parts per million

References

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U.S. EPA, 1990. Demonstration Plan for the Horsehead Resource Development Company Flame Reactor, prepared by the PRC SITE Team for the EPA SITE Program (November).

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Appendix D
HRD Flame Reactor Case Studies

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HRD Flame Reactor Case Studies

Note: This appendix to EPA's Applications Analysis Report was prepared by Horsehead Resource Development Company, Inc. (HRD). Claims and interpretations of results in this Appendix are those made by the vendor and are not necessarily substantiated by test or cost data. Many of HRD's claims regarding cost and performance can be compared to the available data in Section 4 and Appendix C of the Applications Analysis Report.

D.1 Case Study D-1

Material Processed: Steel industry electric arc furnace (EAF) dust (K061)

Material Description: EAF dust is the emission control dust generated from EAF carbon-steel production. The principal components of interest in EAF dust are volatile metals such as zinc, lead, and cadmium, which volatilize from metal scrap during processing. The amount of galvanized scrap, a feed component of EAF steel production, has increased in recent years, increasing the concentration of volatile metals in EAF dust. In EAF steel production, volatile metals and other materials such as some alkali and halide components are collected in the baghouse after cooling and condensing. EAF dust also includes a significant amount of particulate carry-over consisting mainly of flux, slag, and iron oxides. The table below summarizes the range of EAF dust processed at the Monaca, Pennsylvania, Flame Reactor facility. This range of EAF dust compositions is a good representation of the range of composition found in the domestic steel industry.

Range of EAF Dust (K061) Compositions Tested at the Monaca Flame Reactor Facility (percent)

Cadmium	0.01 - 0.12
Calcium	1.3 - 30.8
Chloride	0.26 - 5.0
Chromium	0.1 - 4
Fluoride	0.07 - 1.4
Iron	15.0 - 44.4
Lead	0.5 - 5
Silicon	0.43 - 2.5
Zinc	5 - 40

EAF dust is a listed RCRA hazardous waste due to leachable quantities of lead, cadmium, and chromium. Land disposal restrictions and related regulations require that the majority of EAF dust be recycled for zinc recovery and the production of stable residues. The zinc units recovered are valuable to the domestic zinc industry as feed, avoiding the loss of natural resources.

Test Objectives: EAF dust processing was targeted as the first commercial application for HRD Flame Reactor technology, and several goals were established to achieve this end. The primary objectives of this effort are summarized below.

- The slag product must be nonhazardous according to existing EPA standards and regulations.
- Metal oxide recovery economics must be maximized within the constraints of producing a nonhazardous slag.
- The design and operation of process equipment must be optimized.
- The response of the HRD Flame Reactor technology to variations in EAF dust composition must be evaluated.
- Process capital and operating costs must be determined with enough confidence to estimate commercial costs.

Special Considerations: EAF dust is characteristically a fine, dry material, suitable for HRD Flame Reactor processing without feed preparation. However, dry EAF dust (less than 1.0 percent moisture) is often cohesive or sticky, which can cause bridging in storage vessels and can lead to other solid transport and handling problems. HRD engineered a materials storage and handling system especially suited to EAF dust. Storage vessels have steeply sloped sides and live-bottom feeders to discharge materials in an effective, easily regulated manner with a first-in, first-out inventory. Proper management of solid transport throughout the system permits controlled metering to the HRD Flame Reactor and efficient processing.

Process Tests: Since 1986, the Monaca HRD Flame Reactor facility has processed over 2,200 tons of EAF dust over a wide variety of process conditions. For both solid fuel- and natural gas-fired operations, the following recoveries of metal oxide products have been demonstrated over the full range of EAF dust composition:

- 92 percent zinc recovery
- 95 percent lead recovery
- 99 percent cadmium recovery

A series of tests were conducted in 1987 to generate data for a petition designed to obtain a generic delisting of Flame Reactor slag from EAF dust processing. A testing and sampling plan was designed in conjunction with the EPA, and 240 tons of EAF dust were processed. The EAF dust was obtained from three different generators and contained average to high concentrations of lead, cadmium, chromium, and zinc. The results of these slag delisting tests clearly prove the ability of the HRD Flame Reactor technology to produce an inert slag from EAF dust processing. Results are listed in Table D-1. Note that while the chromium is not volatilized from slag, it is totally encapsulated in a fully vitrified product, and no leaching occurs. (The leach tests are from Extraction Procedure (EP) Toxicity testing, because the work predates the establishment of Toxicity Characteristic Leaching Procedure (TCLP) testing as the standard leach test procedure.)

The HRD Flame Reactor has demonstrated that it is a viable, commercial alternative for processing EAF dusts. It not only recycles zinc, lead, and cadmium, but also produces a delistable slag.

Process Economics: The HRD Flame Reactor technology is easily scaled for regional or on-site EAF dust processing, thereby minimizing transportation and handling costs. Capital and operating costs for 20,000 tons per year (tpy) coal- and natural gas-fired facilities are presented below. Besides material costs and other items listed in Tables D-2 and D-3, the principal assumptions include the following:

- The cost of transporting EAF dust to the plant will be borne by the generator.
- The product oxide requires additional processing at some net cost so that recovered zinc, lead, and cadmium can be converted into salable materials for recycling.
- The product slag will be marketed at a value sufficient to cover transportation costs with no net profit or loss. Slag market opportunities include cement clinker production and traditional aggregate markets.

Table D-1. Slag Delisting Test Results for HRD Flame Reactor Processing of EAF Dust (mg/l)

Analyte	High Chromium EAF Dust	High Lead and Cadmium EAF Dust	Typical EAF Dust	6.3 x Drinking Water Standard
Lead	<0.02	<0.029	<0.02	0.315
Cadmium	<0.01	<0.01	<0.01	0.063
Chromium	<0.015	<0.011	<0.01	0.315

Notes:

mg/L = milligrams per liter

Table D-2. HRD Flame Reactor Process - Capital Cost Estimate Natural Gas-Fired versus Coal-Fired 20,000 Tons of EAF Dust per Year With 19 Percent Zinc

Major Area	Gas-Fired	Coal-Fired
Site Improvements	$ 351,000	$ 351,000
Dust and Fuel Storage and Handling	340,000	472,000
Feed System and Reactor	313,000	360,000
Slag Separator and Handling	178,000	178,000
Fuel Preparation	0	448,000
Oxide Handling and Storage	612,000	612,000
Instrumentation	225,000	225,000
Utilities	877,000	848,000
Buildings	51,000	67,000
Subtotal	2,948,000	4,010,000
Engineering	279,000	337,000
Contingency	335,000	405,000
TOTAL CAPITAL COST	$3,562,000	$4,752,000

Table D-3. HRD Flame Reactor EAF Dust Processing Costs

Cost Factors	Units	$/Unit	Gas Units/Ton	Gas Cost/Ton	Coal Units/Ton	Coal Cost/Ton
Natural Gas	mcf	2.50	9.90	$ 34.65	–	–
Coal	ton	50	–	–	0.379	$ 18.95
Oxygen	100 scf	0.22	125.	31.25	114.	28.50
Labor	man hours	16.00	1.04	18.72	1.46	26.28
Electricity	kilowatt-hours	0.05	225.	11.25	250.	12.50
Materials and Supplies				14.25		17.22
Direct Costs (subtotal)				110.12		103.45
Indirect Costs				5.00		5.00
Capital/Taxes /Royalty				62.84		69.21
Subtotal				177.96		177.66
Zinc Oxide Credits, at $0.50/lb Zinc				(45.00)		(45.00)
NET OPERATING COST				$132.96		$132.66

Notes:

mcf = thousand cubic feet
scf = standard cubic feet

The operating costs for 20,000 tpy gas-fired and coal-fired plants were presented in the Topical Technical Report for the Gas Research Institute, Contract No. 5087-235-1601, in May 1989. These costs appear in Table D-3. Plant staffing is essentially independent of plant size up to about 33,000 tpy. A natural gas-fired plant will require two operators per shift, on a four shift per week basis, supported by a day-shift mechanic and a supervisor. At 40,000 tpy, an additional maintenance mechanic might be necessary. A coal-fired plant would require an additional operator for every shift in which the coal preparation equipment is operated.

Commercialization Status: On April 10, 1991, HRD announced the signing of a long-term processing and site agreement with North Star Steel Co. (NSS). Under the terms of the 10-year agreement, HRD will construct and operate a natural gas-fired HRD Flame Reactor facility to process EAF dust at the NSS mini-mill operation in Beaumont, Texas. The installation will be large enough to accept EAF dust from other Southwestern EAF operations, offering cost savings and improved customer service to other local steel makers. Startup could be as early as the fourth quarter of 1992. HRD is also discussing opportunities for commercial HRD Flame Reactor EAF dust processing with other domestic and foreign steel makers.

D.2 Case Study D-2

Material Processed: Lead blast-furnace slag

Material Description: Lead blast-furnace slag is a residue generated during primary lead smelting. Historically, the slag has been stockpiled on land adjacent to the smelter where it was generated. Lead blast-furnace slag typically exceeds TCLP characteristic hazardous waste standards for cadmium (D006) and lead (D008) but it is exempt from hazardous waste classification by virtue of the 1980 Bevill Amendment. Nonetheless, it is likely that stockpiling of lead blast-furnace slag will be discontinued in the next few years.

Test Objectives: The primary technical objective was to identify operating parameters that would simultaneously produce a clean, nonhazardous slag while recovering enough zinc and lead to produce a recyclable metal oxide product. Sufficient information had to be gathered to develop preliminary capital and operating costs.

Special Considerations: The blast-furnace slag had to be dried and crushed prior to the HRD Flame Reactor process tests. To maximize processing efficiency, the blast-furnace slag was milled by a contract grinding firm to 70 percent by weight finer than 200 mesh.

Process Tests: A total of over 250 tons of two distinctly different lead blast-furnace slags was processed. We refer to them as Slag A and Slag B. Representative analyses are shown in Table D-4.

A small portion of a coarser, screened (not milled) fraction of Slag A was run separately. The overall results allow for a comparison of HRD Flame Reactor performance with milled and screened portions of Slag A, and between Slag A and Slag B, which were both milled. A summary of the results is given in Table D-5, and EP Toxicity test results for lead and cadmium appear in Table D-6.

Process Economics: The capital cost estimate for a HRD Flame Reactor facility to process 100,000 tpy of dry, milled lead blast furnace slag is presented in Table D-7.

Table D-4. Lead Blast Furnace Slag Feed Stock Analyses (percent)

Element	Slag A	Slag B
Cadmium	0.02	0.02
Calcium	7.8	15.1
Carbon	0.1	1.5
Copper	0.2	0.3
Iron	26.7	15.8
Lead	2.0	2.3
Silicon	12.3	12.4
Sulfur	1.7	0.5
Zinc	11.0	10.3

Assumptions include a typical 7-day, four-shift per week operation; slag containing 10 percent zinc; and 30 percent moisture from granulation or field storage. The capital estimate also includes feed drying, milling, and coal preparation equipment.

The operating costs are shown in Table D-8. Labor requirements are estimated at five operators and one foreman per shift, plus three maintenance men and a general foreman. Oxygen-enriched air would be available from a pressure-swing absorption (PSA) unit installed on site by a gas vendor. The miscellaneous category includes nonprocess utilities, outside maintenance, repair parts, and supplies.

Table D-5. Lead Blast Furnace Analytical Results (percent)

	Slag A Screened	Slag A Milled	Slag B Milled
Zinc Recovery to Oxide	49	85	63
Lead Recovery to Oxide	80	95	87
Zinc in Slag	5.87	2.35	5.06
Lead in Slag	0.44	0.18	0.35
Zinc in Oxide	41.6	45.1	–
Lead in Oxide	13.9	10.3	–

Table D-6. EP Toxicity Test Results for HRD Flame Reactor Processing of EAF Dust (mg/l)

Analyte	Average EP Toxicity Test Analyses	Characteristic Hazardous Waste Limit
Lead	1.4	5.0
Cadmium	0.01	1.0

Note:

mg/L = milligrams per liter

Table D-7. HRD Flame Reactor Process - Capital Cost Estimate for Processing 130,000 Tons per Year of Lead Blast Furnace Slag With 10 Percent Zinc and 30 Percent Moisture

Major Area	Installed Cost
Slag Loading, Transportation, and Preparation	$ 4,502,000
Coal Preparation and Handling	2,542,000
Utilities (oxygen and air)	423,000
Reactor, Product Slag Handling	1,111,000
Off-gas and Oxide Handling	1,771,000
Environmental Controls	344,000
Subtotal	10,693,000
Engineering	2,459,000
Contingency	1,315,000
TOTAL PLANT COST	$14,467,000

Commercial Status: HRD is pursuing commercial opportunities for Flame Reactor processing of lead blast-furnace slag.

D.3 Case Study D-3

Material Processed: Neutral leach residue from electrolytic zinc production

Material Description: In electrolytic zinc production, a crude zinc oxide produced from calcining or roasting zinc concentrates is leached with weak sulfuric acid to produce a zinc sulfate solution. Zinc metal is subsequently extracted from the zinc sulfate solution by electrolysis. The leaching step is usually referred to as the neutral leach, because most plants follow it with additional leaching steps using more concentrated acid solutions.

The neutral leach residue is filtered from the zinc sulfate liquor and undergoes limited washing. The raw residue contains 25 to 40 percent moisture. The residue typically contains 6 to 12 percent zinc (dry basis) as uncalcined zinc sulfide and zinc ferrite, as well as zinc sulfate not removed through washing. The residue also contains lead and cadmium, and it often contains economically significant quantities of precious metals.

Test Objectives: The objectives of the HRD Flame Reactor process tests were 1) to maximize the recovery and value of the metal components and 2) to produce a nonhazardous slag byproduct.

Special Considerations: Neutral leach residue must be dried and pulverized prior to processing in the HRD Flame Reactor. A wet scrubber is required to remove sulfur dioxide from the off-gas.

Depending on the particular electrolytic zinc plant, neutral leach residue is either sold as a byproduct for the metal it contains or is releached under more aggressive conditions, as mentioned above. In the first case, the byproduct value is

Table D-8. HRD Flame Reactor Processing Costs

Cost Factors	Units	$/Unit	Units/Ton	Cost/Ton
Coal	ton	50.00	0.30	$ 15.00
Natural gas	mcf	3.50	1.90	6.65
Oxygen - PSA Rental				9.60
Labor	man hours	18.00	0.63	11.34
Electricity	kilowatthours	0.05	295.	14.75
Materials and Supplies	7 percent of capital per year			10.13
Direct Costs (subtotal)				67.47
Indirect Costs				2.00
Capital and Taxes				57.10
Subtotal				126.57
Zinc Oxide Credits, at $0.50/lb Zinc				(22.50)
NET PROCESSING FEE				$104.07

Notes:

mcf = thousand cubic feet
PSA = Pressure swing absorption unit

set at a heavily discounted rate, well below the full value of the metals it contains. In the second case, nearly all of the metals are extracted using hot, strong acid leaching. However, unwanted species are also leached, most notably iron, which must be removed from the zinc sulfate liquor. Several techniques for iron precipitation are used for purification, but all of the precipitates contain hazardous levels of leachable heavy metals such as lead and cadmium.

Process Tests: Three separate test programs were conducted, using neutral leach residue from two separate, domestic electrolytic zinc plants. For each program, the raw residue was dried and crushed by third parties. The use of different vendors for the feed preparation allowed an evaluation of the effect of feed particle size on process performance. Both solid fuel- and natural gas-fired process testing were performed.

The process testing results are summarized in the table below. In addition, when the feed particle size distribution (PSD) was reduced from 80 percent by weight finer than 350 microns to 80 percent less than 75 microns, zinc recovery increased by an average of 10 percent for a given set of operating conditions. Lead and silver recoveries also improved, but to a lesser extent.

Neutral Leach Residue Results

Metal Recoveries to Oxide

Lead	99 percent
Silver	90 percent
Zinc	90 percent

Slag TCLP Extraction Tests

Arsenic	0.29 mg/L
Barium	13.2 mg/L
Cadmium	<0.02 mg/L
Chromium	<0.1 mg/L
Lead	<0.2 mg/L
Mercury	<0.1 mg/L
Selenium	<0.25 mg/L
Silver	<0.01 mg/L

Note: mg/L = milligrams per liter

Process Economics: Capital cost and processing fee breakdowns are shown in Table D-9 and Table D-10, respectively. The capital costs are for a 20,000 tpy coal-fired Flame Reactor on a brownfield site (an already developed industrial site). The plant includes drying and grinding equipment for the neutral leach residue, coal grinding equipment, and a off-gas scrubber for sulfur dioxide.

Energy consumption for drying and crushing is included in the natural gas and electrical costs. Materials and supplies costs are estimated at 7 percent of the capital cost per year. Capital and taxes include financing the plant capital at 12 percent interest over 10 years. Zinc credits are based upon 90 percent recovery of zinc as oxide at 25 percent of the stated zinc price.

Commercial Status: HRD is pursuing an opportunity for commercial processing of neutral leach residue.

Table D-9. HRD Flame Reactor Process - Capital Cost Estimate for Processing 20,000 Tons per Year of Neutral Leach Residue with 10 to 12 Percent Zinc and 30 Percent Moisture

Major Area	Installed Cost
Feed and Coal Preparation	$ 1,580,000
Feed and Coal Storage	250,000
Reactor, Feed System	350,000
Product Slag Handling	328,000
Off-gas and Oxide Handling	875,000
Electrical and Controls	752,000
Buildings and Utilities	293,000
Subtotal	4,428,000
Engineering	1,085,000
Contingency	667,000
TOTAL PLANT COST	$ 6,200,000

D.4 Case Study D-4

Material Processed: Goethite iron precipitation residue from electrolytic zinc plant purification circuits

Material Description: Goethite is an amorphous, hydrated, iron precipitate formed during the purification of zinc sulfate liquor. It is removed from the liquor by filtration, followed by limited washing. Goethite contains 6 percent to 10 percent zinc as sulfate.

Test Objectives: Along with a significant amount of zinc, goethite often contains hazardous levels of leachable cadmium and sometimes lead. These HRD Flame Reactor process tests were directed at 1) maximizing zinc recovery and 2) rendering a nonhazardous slag byproduct.

Special Considerations: Goethite iron requires drying and crushing prior to processing in the Flame Reactor.

Process Tests: Two test programs were performed. Representative results are presented below.

Goethite Test Results

Metal Recoveries to Oxide

Lead .... 93 percent
Zinc .... 77 percent

Slag TCLP Extraction Tests

Arsenic .... <0.02 mg/L
Barium .... 0.13 mg/L
Cadmium .... <0.01 mg/L
Chromium .... <0.01 mg/L
Lead .... 0.1 mg/L
Mercury .... <0.001 mg/L
Selenium .... <0.03 mg/L
Silver .... <0.02 mg/L

Process Economics: A breakdown of the capital cost for a 50,000 tpy natural gas-fired Flame Reactor appears in Table D-11. The costs assume brownfield construction to take advantage of existing infrastructure. The goethite iron is

Table D-10. HRD Flame Reactor Processing Costs for Neutral Leach Residue Processing

Cost Factors	Units	$/Unit	Units/Ton	Cost/Ton
Coal	ton	50.00	0.44	$ 22.00
Oxygen	100 scf	0.25	154.	38.50
Natural Gas	mcf	3.50	3.20	11.20
Labor	man hours	18.00	1.46	26.28
Electricity	kilowatthours	0.05	389.	19.45
Materials and Supplies				21.70
Direct Costs (subtotal)				139.13
Indirect Costs				5.00
Capital and Taxes				85.49
Subtotal				229.62
Zinc Oxide Credits, at $0.50/lb Zinc				(36.00)
NET PROCESSING FEE				$183.82

Notes:

mcf = thousand cubic feet
scf = standard cubic feet

Table D-11. HRD Flame Reactor Process - Capital Cost Estimate for Processing 50,000 Tons per Year of Iron Precipitate (Goethite) with 12 Percent Zinc and 30 Percent Moisture

Major Area	Installed Cost
Feed Preparation and Storage	$ 2,466,000
Reactor, Feed System	523,000
Slag Handling	447,000
Off-gas and Oxide Handling	1,399,000
Electrical and Utilities	1,750,000
Buildings and Site Improvements	397,000
Subtotal	6,982,000
Engineering	700,000
Contingency	768,000
TOTAL PLANT COST	$ 8,450,000

dried to a fine powder in a spray drier, and a wet scrubber is used to strip sulfur dioxide from the tail-gas.

The cost components of the processing fee are shown in Table D-12. Oxygen-enriched air will be supplies by a leased PSA unit; energy consumption for the PSA unit is included in the electrical costs. Materials and supplies costs are estimated at 7 percent of the capital cost per year. Capital and taxes include financing the plant capital at 12 percent interest over 10 years. Zinc credits are based upon 90 percent recovery of zinc in the oxide and 25 percent of the stated zinc price.

Commercial Status: HRD has made a proposal for a Flame Reactor facility to process 50,000 tpy of goethite in Bartlesville, Oklahoma. The plant would dry and crush the goethite iron and would excavate and process stockpiled material.

D.5 Case Study D-5

Material Processed: Brass foundry Wheelabrator dusts

Material Description: The material consists of brass foundry sands collected from casting cleaning operations. The metal content, mainly copper and copper alloy, is usually around 5 to 10 percent by weight, but some of the material collected for these tests contained up to 45 percent metal by weight. The material often does not meet characteristic hazardous waste criteria for lead (D008) or cadmium (D006).

Test Objectives: Recover volatile metal components as a mixed metal oxide product, recover nonhazardous slag byproduct, and investigate the production of a copper alloy product.

Special Consideration: Because of the high silicate content, sand had to be added to the Wheelabrator dust as a fluxing agent in order to obtain a fluid slag. Sand particles were much coarser than typical HRD Flame Reactor feed, making this process more difficult, because there is very little time to melt large particles in the reactor. After trying several fluxing agents, iron oxide was determined to yielded the best slag properties. EAF dust was chosen as the iron-rich fluxing agent.

Process Tests: As shown in the data table below, the Flame Reactor product slag easily met EP toxicity criteria for a nonhazardous waste. A molten copper alloy was readily collected with the slag.

Table D-12. HRD Flame Reactor Processing Fees

Cost Factors	Units	$/Unit	Units/Ton	Cost/Ton
Natural Gas	mcf	3.50	16.80	58.80
Oxygen - PSA Rental				19.20
Labor	man hours	18.00	0.79	14.22
Electricity	kilowatthours	0.05	471	23.55
Materials and Supplies				12.88
Direct Costs (subtotal)				128.65
Indirect Cost				3.00
Capital and Taxes				63.85
Subtotal				195.50
Zinc Oxide Credits, at $0.50/lb Zinc				(27.00)
NET PROCESSING FEE				$168.50

Notes:

mcf = thousand cubic feet
PSA = Pressure swing absorption unit

Slag EP Toxicity Leach Tests

Arsenic	<0.01 mg/L
Barium	0.05 mg/L
Cadmium	<0.004 mg/L
Chromium	<0.006 mg/L
Lead	0.13 mg/L
Mercury	<0.002 mg/L
Selenium	<0.01 mg/L
Silver	<0.01 mg/L

Process Economics: The capital costs for a Flame Reactor facility to process 12,000 tpy of brass foundry sand appear in Table D-13. The scenario includes processing EAF dust at a 1:1 ratio with foundry sand, as described above. Therefore, the Flame Reactor capacity is 24,000 tpy of feed. Equipment for excavating and drying the sand is included.

The processing fee breakdown in Table D-14 reflects only the foundry sand processing fee. Energy costs for drying are included. Materials and supplies costs are estimated at 7 percent of the capital cost per year. Capital expenses and taxes include financing the plant capital at 12 percent interest over 10 years. It is assumed that the foundry sand contains 15 percent copper, and that 65 percent is recovered as alloy, valued at 40 percent of the stated price of copper. The foundry sand does not contain sufficient zinc for an oxide credit.

Commercial Status: Foundry sand processing economics are very sensitive to the availability of a low cost flux. HRD has made a proposal for remediation of foundry sand landfilled at a brass foundry site.

D.6 Case Study D-6

Material Processed: EAF dust spiked with CCl_4

Material Description: CCl_4 was fed into the Flame Reactor simultaneously with steel mill EAF dust in order to simulate a metal-bearing waste contaminated with hazardous organic compounds.

Test Objectives: The purpose of this test was to demonstrate the ability of the Flame Reactor process to destroy hazardous organic contaminants in conjunction with the treatment of metal-bearing wastes.

Special Considerations: The CCl_4 was injected separately from the EAF dust to avoid fouling the pneumatic injection system. The CCl_4 was introduced at the same point in the process, but through a port offset from the solid feed by 90 degrees.

Process Tests: The CCl_4 was fed at a rate equivalent to 5 percent of the total feed. The average destruction removal efficiency (DRE) was 99.9986 percent, and no CCl_4 was detected in either the slag or oxide products. The test data are summarized in the table below.

Test Results

EAF dust feed rate	2400 lb/hr
CCl_4 feed rate	126 lb/hr
CCl_4 in total feed	5 percent
CCl_4 DRE	99.9986 percent
CCl_4 in slag product	< 800 ng/kg
CCl_4 in oxide product	< 800 ng/kg
CCl_4 in off-gas	9.21x10-10 lb/dscf
CCl_4 emission rate	1.01x10-3 lb/hr

Notes:

ng/kg = nanograms per kilogram
lb/hr = pounds per hour
lb/dscf = pounds per dry standard cubic foot

This program demonstrated the ability of the Flame Reactor technology to effectively destroy hazardous organic contaminants in metal-bearing wastes.

Process Economics: The sampling, monitoring, and analysis costs for organic chemicals will be higher than for materials containing only toxic metals. The capital costs should not be much higher than for similar materials without organic chemicals. However, the costs of organic analyses could significantly impact processing costs, depending on the compounds involved.

Commercial Status: HRD is pursuing opportunities to apply the Flame Reactor technology to treat metal-bearing wastes contaminated with organic chemicals. Several wastes are under review for process testing.

D.7 Case Study D-7

Material Processed: Secondary lead smelter (SLS) soda slag fluxed with silica flour

Material Description: The material was obtained from the same 72-ton lot of SLS slag processed in the SITE demonstration test.

Table D-13. HRD Flame Reactor Process - Capital Cost Estimate for Processing 12,000 Tons per Year of Brass Foundry Sand per Year Fluxed with EAF Dust

Major Area	Installed Cost
Feed Preparation and Storage	$ 1,900,000
Reactor, Feed System	350,000
Slag Handling	370,000
Off-gas and Oxide Handling	550,000
Electrical and Utilities	1,050,000
Buildings and Site Improvements	470,000
Subtotal	4,690,000
Engineering	940,000
Contingency	470,000
TOTAL PLANT COST	$ 6,100,000

Table D-14. HRD Flame Reactor Processing Fees

Cost Factors	Units	$/Unit	Units/Ton	Cost/Ton
Natural Gas	mcf	3.50	8.39	29.37
Oxygen	100 scf	0.25	113.4	28.35
Labor	man hours	18.00	1.21	21.78
Electricity	kilowatthours	0.05	310	15.50
Materials and Supplies				17.79
Direct Costs (subtotal)				112.79
Indirect Cost				5.00
Capital and Taxes				75.90
Subtotal				193.69
Copper Credits, at $1.00/lb Copper				(78.00)
NET PROCESSING FEE				$115.69

Notes:

mcf = thousand cubic feet
scf = standard cubic feet

Table D-15. Test Summary

	0 % Silica	12.5 % Silica	25 % Silica
Lead in Slag	1.12%	0.69%	0.69%
Lead in Oxide	19.1%	17.4%	17.5%
Lead Recovered to Oxide	91%	95%	97%
Slag TCLP, Lead	<0.33[a] mg/L	0.20 mg/L	<0.20 mg/L
Slag TCLP, Arsenic	0.474[a] mg/L	<0.13 mg/L	<0.13 mg/L

Notes:

[a] Chemical analyses done by Versar, Inc. on demonstration test samples; all other data are from analyses by HRD.
mg/L = milligrams per liter.
% = percent.

Test Objectives: The purpose of this test was to make a more durable Flame Reactor product slag by adding silica flour (ground sand) as a fluxing agent. No attempt was made to optimize the flux addition in terms of composition, quantity, or cost.

Special Considerations: As in the SITE demonstration test, SLS slag had to be dried and crushed prior to Flame Reactor processing. Also, silica flour flux was blended with the SLS slag during feed preparation so that the materials would be well mixed before processing.

Process Tests: The SLS slag was fluxed with 12.5 and 25 percent silica flour. (The flux addition is calculated as follows: [percent flux] = [100 percent] x [lb of flux] / [lb of SLS slag].) A summary of the results is given in Table D-15.

TCLP data show that adding silica flour to the SLS slag did not reduce the Flame Reactor effectiveness in detoxifying the material. In fact, in the case of arsenic, TCLP performance was improved over the 0.474 mg/L average for the unfluxed material in the SITE demonstration test.

Fluxing with 25 percent silica flour produced a firm, glassy slag that does not disintegrate on contact with water. This product slag should be suitable for distribution in aggregate markets as bituminous sand for asphalt. The SLS slag fluxed with 12.5 percent silica flour did not remain firm and disintegrated on contact with water.

Process Economics: The operating costs for the commercial scenario are presented in Appendix B (Vendor's Claims) of this report and are repeated in Table D-16, with the exception that the SLS slag is fluxed with 25 percent silica

Table D-16. HRD Flame Reactor Processing Fees

Cost Factors	Units	$/Unit	Units/Ton	Cost/Ton
Natural Gas	mcf	3.50	8.62	30.15
Oxygen	100 scf	0.25	189.3	47.31
Labor	man hours	25.00	1.41	35.20
Electricity	kilowatthours	0.05	305.	15.25
Flux	tons	55.00	0.25	13.75
Materials and Supplies				17.37
Direct Costs (subtotal)				159.04
Indirect Cost				5.00
Capital and Taxes				74.88
Subtotal				238.92
Product Oxide Shipping and Recycling				19.00
Product Slag Handling and Marketing				0.00
NET PROCESSING FEE				$257.92

Notes:

mcf = thousand cubic feet
scf = standard cubic feet

flour. Instead of disposal in a nonhazardous landfill, the product slag is marketed as an aggregate at a value sufficient to cover handling and transportation, resulting in no net profit or loss.

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